INNOVATIVE TECHNOLOGIES AND CURRENT TRENDS
IN SCIENCE AND MATHEMATICS EDUCATION

Editors
Dr. Serpil KARA
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Innovative Technologies and Current Trends in Science and Mathematics Education

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PREFACE

The rapid advance of technology in recent years has influenced not only how we relate and communicate, but also the fundamental principles of teaching, learning, and scientific research. Innovative Technologies and Current Trends in Science and Mathematics Education a recent and important addition to this constantly developing topic is education, which provides a thorough examination of the ways in which contemporary technology has impacted scientific and math instruction around the globe. This volume brings together the work of distinguished scholars and educators who critically examine the intersection of technology, pedagogy, and disciplinary content.

Every chapter in this book was chosen after peer review based on its innovative viewpoint, academic rigor, and capacity to impact classroom practice and theoretical knowledge. When taken as a whole, these chapters paint a complex picture of the global movement toward technologically enhanced education and provide new perspectives on how science and math education may develop in the future. We would like to express our profound appreciation to the authors, reviewers, and editorial staff whose commitment and academic quality have enabled this publication. We express our gratitude to the scholars, educators, and policymakers who will continue to influence education in the future as a result of their engagement with these concepts.

This volume is intended to be a resource for current scholarly research as well as a source of motivation for teachers who are working to improve the effectiveness, equity, and engagement of science and math instruction through the thoughtful introduction of technology.

August 2025

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ABOUT THE BOOK

Innovative Technologies and Current Trends in Science and Mathematics Education is a peer-reviewed scholarly work that brings together contemporary research, practice and perspectives on the integration of technology in science and mathematics education. The book addresses the urgent need to rethink traditional pedagogical approaches in light of emerging digital tools, artificial intelligence, immersive environments, and data-driven instruction.

Divided into two thematic sections, the book offers eight chapters written by researchers and educators from various disciplines. Topics include the use of artificial intelligence to foster creative problem solving in mathematics, augmented and virtual reality applications in science education, gamification and digital simulations in classroom settings, and the implications of learning analytics for decision-making in education.

Each chapter aims to bridge theory and practice by providing support for how innovative technologies can increase student engagement, support differentiated instruction, and promote deeper understanding of scientific and mathematical concepts.

Designed for a broad academic audience, including researchers, teacher educators, graduate students, instructional designers, and educational policymakers, this book serves as both a reference and a catalyst for future innovation. The international scope of the contributions also provides a rich and diverse perspective on global educational trends and challenges.

As educational environments continue to evolve, Innovative Technologies and Current Trends in Science and Mathematics Education stands as a valuable resource for those committed to advancing the quality and relevance of education through the thoughtful integration of technology.

ARTIFICIAL INTELLIGENCE AND APPLICATIONS IN SCIENCE EDUCATION

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Introduction

The concept of Artificial Intelligence (AI) has been defined by various scientists and researchers from different perspectives. AI is a field of science that aims to simulate human-like cognitive processes and structure intelligent systems (Görz & Nebel, 2005). AI can be defined as a computer or computer-assisted machine with human-like characteristics. Such systems have the ability to perform tasks such as problem-solving, comprehension, inference, generalization and learning from past experiences, all of which are high-level logical processes similar to human capabilities (Nabiyev, 2012). AI is also a tool that ensures the meaningful organization of the vast knowledge accumulated in program databases (Ayık et al., 2007).

Coşkun & Gülleroğlu (2021) defined AI in their study as a field of computer science focused on the creation of intelligent machines capable of imitating human abilities to think and act. In their 2019 report, the European Commission's High-Level Expert Group on Artificial Intelligence defined AI as "systems that exhibit intelligent behaviors by analyzing their environment and performing actions with a certain degree of autonomy to achieve specific goals" (Hleg, 2019). The Turkish Language Association, on the other hand, defines AI as "the ability of a computer, a robot controlled by a computer, or a programmable device to perform functions such as perception, learning, reasoning, decision-making, problem-solving and communication, similar to human abilities" (Turkish Language Association, 2024).

Based on these various definitions, AI can be defined as systems that attempt to imitate certain mental traits and abilities of humans through computers or other artificial systems, exhibiting artificially created intelligent behaviors.

One of the main objectives of AI is to enable humans to perform difficult or repetitive tasks more efficiently and effectively. Particularly, the automation of repetitive and time-consuming tasks can allow individuals to focus on more creative and strategic endeavors. In the field of education, AI technologies can help personalize learning processes, thereby enhancing students' potential. In general, AI technologies have been developed to simplify human life, improve business processes, and overcome challenges in various domains. The advantages offered by these technologies have made them an indispensable part of the modern world. The contributions of AI can be broadly summarized as follows (Khanzode & Sarode, 2020) (Figure 1).

Figure 1. *Contributions of AI*

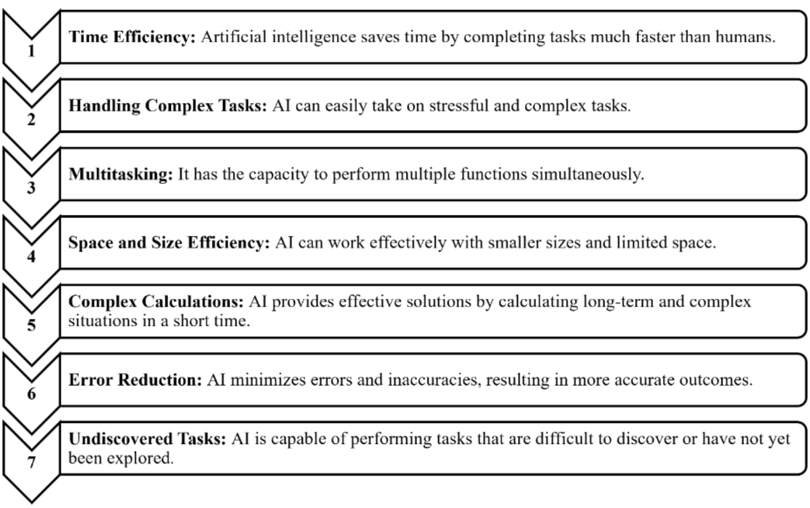
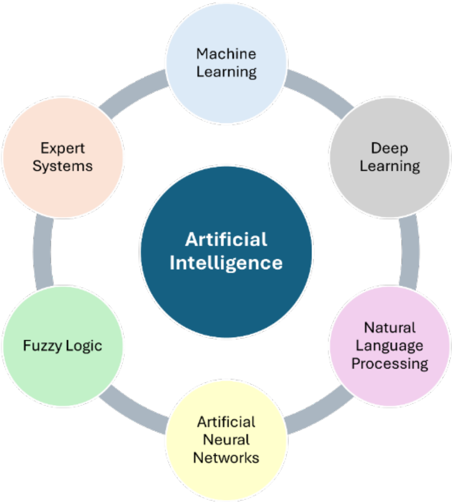


Figure 2. *Subfields of Artificial Intelligence*



Deep learning

Deep learning is a subfield of artificial intelligence that uses multi-layered neural networks to analyze complex data structures, make predictions, or make decisions (Arslan, 2024). Inspired by the functioning of the brain and nerve cells, deep learning algorithms aim to learn, generalize and infer by modeling the characteristics of neurons, such as processing and transmitting information. The human neural network is a biological system composed of many neurons with inputs and outputs, along with the connections between them. As a subdiscipline of machine learning, deep learning operates with similarly structured neural networks that function like the neurons in the human brain, essentially modeling biological nerve cells and their principles of operation (Göçmez, 2023). Deep learning trains neural networks using large datasets, enabling computers to process visual information at a human level and in some cases, even surpass human performance (Yuan et al., 2024). The performance of deep learning models has been found to increase in proportion to the amount of training data (Hestness et al., 2017). This explains why deep learning has become so significant in the age of big data. Deep learning algorithms are widely used, particularly in computer vision and natural language processing fields.

Natural language processing

Natural Language Processing (NLP) is a field of artificial intelligence concerned with the understanding, interpretation and generation of human language by computers (Jurafsky & Martin, 2025). NLP is a technology that uses natural language to enable communication with computers. The primary goal of natural language processing is to enable computers to communicate more effectively with humans by understanding data in natural language (Young et al., 2018). The key to processing natural language is allowing computers to understand it; thus, it is also referred to as computational linguistics, a field at the intersection of language information processing and artificial intelligence (Göçmez, 2023). NLP techniques are used in seven distinct areas: grammar and semantic analysis, information extraction, text mining, information retrieval, machine translation, question-answering systems, and dialogue systems (Zhang et al., 2020; Zhang & Lu, 2021). Applications of natural language processing include machine translation, speech recognition, sentiment analysis, question-answering systems, and chatbots (Liu et al., 2019).

Artificial neural networks

Artificial Neural Networks (ANNs) are powerful computational models used for tasks such as data processing and pattern recognition, aiming to mimic the neural structure and function of the human brain (Guo et al., 2016). In terms of their operational principle, input data is processed, weight and bias values are calculated, and the system attempts to reach specific outputs (Goodfellow et al., 2016). This process occurs in a manner similar to the way the human brain processes information. Artificial neural networks are particularly effective at extracting meaningful results from complex or uncertain data. They are frequently used in areas such as supervision, speech and image recognition and processing, prediction, system modeling, and the monitoring, recognition, and interpretation of physiological signals (Smith, 2005; Elmas, 2021).

Fuzzy logic

Fuzzy logic is a method used to eliminate uncertainties in verbal expressions, even though complex thoughts and situations encountered in the real world cannot be numerically expressed (Uygunoğlu & Ünal, 2016). Unlike traditional computer languages, which rely on binary values of 0-1, or the binary opposites found in human logic such as hot-cold or long-short, fuzzy logic operates on intermediate values, such as hot-warm-cold or long-medium-short (Elmas, 2021). In classical logic, a statement is either true or false, whereas in fuzzy logic, a statement has a degree of truth (Wang & Mendel, 2017). The aim of using fuzzy logic is to develop systems that can think, make decisions and choose like humans (Atalay & Çelik, 2017). This characteristic allows fuzzy logic to model real-world problems more effectively (Castillo & Melin, 2018). Today, fuzzy logic has a wide range of applications in fields such as artificial intelligence, control systems, and decision support mechanisms (Wang et al., 2018).

Expert systems

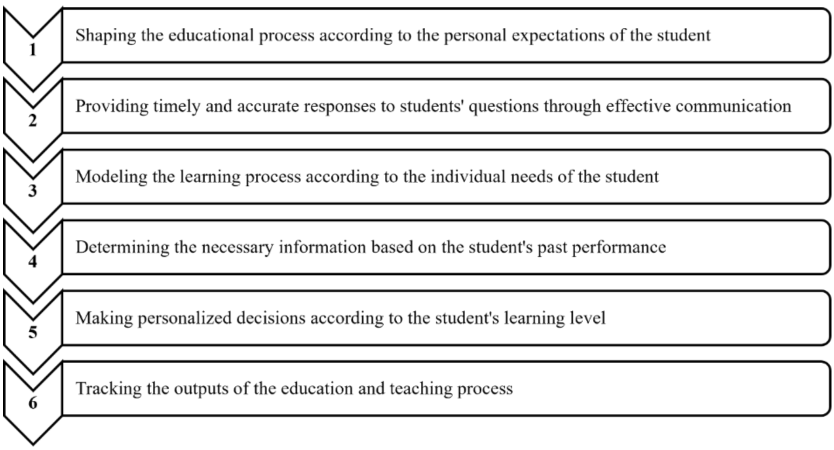
An expert system is essentially a software processed by a computer with the aim of simulating human thought. Expert systems are knowledge-based systems that transfer the accumulated knowledge and experience of individuals with deep expertise in a specific subject to a digital environment, offering solutions to encountered problems, errors or issues (Şahin, 2008). In the problem-solving process, expert systems mimic the knowledge and logical inference mechanisms used by experts (Pirim, 2006). The development of expert systems requires the creation of a comprehensive knowledge base relevant to the field. Effective expert system should consist of four fundamental modules: knowledge base, knowledge update, user interface and inference or decision mechanism (Önder, 2003).

Artificial Intelligence and Education

Artificial Intelligence in education refers to the use of advanced technological tools that imitate human intelligence to enhance learning and teaching processes. AI in education is an interdisciplinary field that combines computer science, education and psychology (Burtgil, 2024). The primary goal of this technology is to design and develop interactive and adaptable learning environments for all age groups and subject areas. The education sector holds significant potential for the integration of AI technologies (Küçükali & Coşkun, 2021).

The features that distinguish artificial intelligence technologies in education from other educational technologies can be listed as follows (Owoc et al., 2019) (Figure 3).

Figure 3. *The features that distinguish artificial intelligence technologies from other educational technologies*



AI technology offers personalized educational programs tailored to individuals' abilities, skills and interests, thereby expanding educational opportunities for various age groups. By identifying and adapting to each student's specific educational needs, AI creates personalized learning experiences (Güzey et al., 2023). Given the rapid advancements in AI technology, it is expected that this technology will significantly impact educational systems and their key components, such as teachers, students, administrators and parents, in the near future (Çetin & Aktaş, 2021). In the transforming educational system, students will need to understand, transform, and synthesize information in virtual environments. To achieve these goals, students must acquire in depth knowledge of AI. Therefore, the use of AI not only increases efficiency in education but also better addresses the individual learning needs of students. As a result, this process generally enhances educational quality and improves student success.

Artificial Intelligence Education in the World

Artificial Intelligence, which aims to understand, analyze and even simulate human behavior by developing data-driven intelligent machines, is becoming a global phenomenon across all industries, including the education sector. In this regard, some of the world's largest economic powers are experimenting with new techniques to integrate AI into their education systems, striving to gain leadership in the field of educational technologies (Zhao et al., 2020). Many countries are working on the development of AI technologies in light of the advantages these applications offer. In this context, AI applications are expected to grow significantly in the future, with global spending expected to reach 6 billion dollars by 2025 (Kurt, 2024). Studies conducted by countries around the world reveal that AI education is being offered as a mandatory or elective subject, especially at the middle school level. In order to help students use AI more efficiently in their daily lives and adapt more easily to these technologies, educational institutions and organizations are creating appropriate AI tools and environments and various projects are being implemented in this process (Nabiyev & Erümit, 2020).

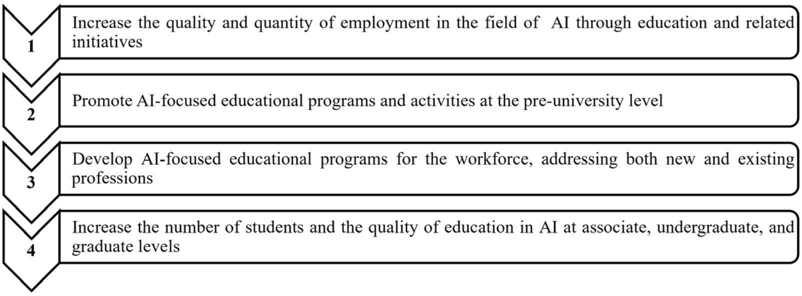
The Artificial Intelligence Policy Association (AIPA) presented the AI in Education Policy Document in December 2023, considering the views of experts from various disciplines. Countries such as China and the United States are investing a significant portion of their Gross Domestic Product (GDP) in artificial intelligence (Kurt, 2024). Germany, Jordan, Bulgaria and Saudi Arabia are in the process of developing AI curricula. Armenia, Austria, Belgium, China, India, South Korea, Kuwait, Portugal, Qatar, Serbia and the United Arab Emirates have established AI education programs, which have been approved by their respective governments (UNESCO, 2022). In Dubai, United Arab Emirates, the world's first Artificial Intelligence University began offering education in 2020. McGraw-Hill, based in the United States, developed ALEKS, an adaptive AI education software. The University of Science and Technology of China in Hefei has opened an Artificial Intelligence School. In the United States, the Massachusetts Institute of Technology (MIT) has established an Artificial Intelligence College. The Republic of Korea aims to produce 5,000 AI graduates annually by 2030, with a target of training a total of 50,000 AI experts (Koç, 2024).

Considering the efforts of these nations and organizations, it is possible to predict the future effectiveness of artificial intelligence in the field of education. In this context, it is necessary to increase artificial intelligence research in Türkiye's education sector.

Artificial Intelligence Education in Türkiye

Artificial Intelligence in education plays a crucial role in enhancing quality, monitoring educational processes and developing adaptive systems. AI can assist teachers, automate information assessments, analyze student behaviors and provide personalized learning systems. The contributions of AI in education and its rapid global development have laid the groundwork for significant steps to be taken in Türkiye regarding AI. With the official start of the Presidential Government System in 2018, digitalization and AI became key agenda items, leading to the establishment of the Presidential Digital Transformation Office (PDTO). As the main actor in digital transformation, the PDTO has played an active role in implementing AI-related initiatives in government institutions. In 2019, the "Big Data and Artificial Intelligence Applications Department" was established under the PDTO (T.C. Presidential Digital Transformation Office, 2021, p. 39). In parallel with these developments, the TÜBİTAK Artificial Intelligence Institute was founded in 2020 and in 2021, the PDTO published the National Artificial Intelligence Strategy Document. The key goals for AI education in Türkiye, as outlined in this document, can be summarized as follows (T.C. Presidential Digital Transformation Office, 2021; Tokatlı, 2024) (Figure 4)

Figure 4. *AI education Goals in Türkiye*



In alignment with global higher education curricula, AI education in Türkiye has been offered for many years at the university level under various headings, such as "Introduction to Artificial Intelligence" and "Machine Learning," within different engineering faculties. The Council of Higher Education, the official body responsible for regulating and overseeing higher education in Türkiye, announced in March 2024 that five undergraduate programs and twelve new associate degree programs focusing on AI, digitalization and big data would be introduced for the first time in universities (T.C. Council of Higher Education, 2024). At the middle school level, the Ministry of National Education began offering an elective course titled "Artificial Intelligence Applications" for 7th and 8th-grade students in the 2023-2024 academic year. In November 2023, it was announced on the Ministry of National Education's official website that the curriculum for this course had been approved (T.C. Ministry of National Education, 2023a). According to the Global AI Index published on September 19, 2024, Türkiye ranks 34th. This highlights the need for AI to develop more actively across all sectors in Türkiye.

Artificial Intelligence in Science Education

Science is defined as a natural science that helps individuals understand and interpret the world around them (Hançer et al., 2003). It is essential for individuals and societies to be scientifically literate to comprehend and utilize contemporary knowledge and technological advancements in a rational manner (Özdemir, 2010). According to Köseoğlu & Kavak (2001), when teaching science, educators should guide students in areas such as investigating, questioning and examining phenomena and situations, asking useful and creative questions, developing meaningful expressions about the natural and technological contemporary world and explaining how scientific knowledge is acquired. For science education to achieve these objectives, selecting appropriate teaching strategies during the educational process is of paramount importance. In this context, contemporary teaching methods should be used to stimulate students' creativity and suitable tools should be provided to foster the development of scientific process skills (Gürdoğan, 2020). One of the tools that is increasingly being used in education today is AI.

AI is increasingly used as a significant tool in science education, aimed at enhancing students' scientific process skills and enriching their learning experiences. AI can be integrated into science teaching in various ways, aiding educators in making their teaching processes more effective (Kotsis, 2024). AI offers personalized learning experiences by considering the individuality of students. By delivering content based on students' learning speed, needs and interests, it enhances the efficiency of learning. In complex and multifaceted subjects such as science, this approach enables students to gain a deeper understanding of the topics (Olatunde-Aiyedun, 2024).

AI continuously monitors students' performance and identifies challenges encountered during the learning process. This allows teachers to intervene in areas where students may be struggling. Furthermore, AI systems provide immediate feedback to students, helping them quickly correct misunderstandings or conceptual errors (Izadi & Forouzanfar, 2024). Experimental learning is essential in science education. AI facilitates the safe presentation of real-world experiences through simulations and virtual laboratories in a virtual environment. As a result, students can observe various scientific experiments and natural phenomena in a virtual setting, gaining practical knowledge (Constantinescu et al, 2024).

AI-supported applications and platforms have the potential to make science curriculum topics more interactive. Through intelligent educational tools, students can access more dynamic and learning-oriented content. These tools help students develop creative thinking and problem-solving skills (Abrar et al., 2025). Science educators can enhance the efficiency of their teaching processes with the help of AI technologies. AI can assist teachers in lesson planning, tracking student progress and preparing instructional materials. Additionally, it enables teachers to develop appropriate teaching methods for students at different levels within the classroom (Chen et al., 2020). Furthermore, AI can foster the development of students' creative thinking abilities. Discoveries and innovative ideas in science often rely on creative thinking processes. AI can guide students through these processes, encouraging them to explore new solutions and discover alternative approaches (Walter, 2024).

In conclusion, the integration of artificial intelligence in science education plays a crucial role in enabling students to access scientific knowledge more effectively and in greater depth. AI offers student-centered, innovative and dynamic learning environments, contributing to higher success and lasting learning outcomes in education.

Advantages of Using Artificial Intelligence in Science Education

The integration of AI into the educational system has become a significant focal point in both academic research and educational approaches. The use of AI in education presents various advantages and disadvantages. AI can provide students with personalized learning experiences, which may encourage higher engagement rates and improved academic performance (Shen et al., 2021). Additionally, AI technologies facilitate key processes for school administrators, teachers and students, offering considerable ease in fulfilling their responsibilities (Humphry & Fuller, 2023). AI can automatically track and assess students' progress, automate grading processes, provide rapid feedback and assist teachers in adapting instructional methods based on this feedback (Akgun & Greenhow, 2022). The importance of rapid and effective feedback, highlighted in Hattie & Timperley's (2007) research, is critical for individual development.

It is possible to prepare instructional materials and study plans tailored to students' educational levels and learning needs. To provide personalized support and guidance, AI-powered chatbots can respond to frequently asked questions, offer feedback on assignments and suggest additional study materials based on students' performance (Akinwalere & Ivanov, 2022). AI-based learning systems can analyze data related to students' learning styles, speeds and preferences, offering customized learning experiences. This approach enhances student motivation and facilitates a more effective learning process (Kurt, 2024).

Artificial intelligence can assist educators in identifying the most effective teaching methods and materials for improving learning outcomes. This data can be used to develop and refine curricula, leading to better student performance (Al Nabhani et al., 2025). AI systems enable the creation of personalized curricula and content tailored to the specific needs of students. The automation of assessment and feedback processes by AI significantly reduces the workload of educators. AI-powered systems are designed to enhance academic success, especially in complex subjects. AI algorithms that accurately assess tasks and exams make significant contributions to the educational process (Kandlhofer et al., 2016). Furthermore, AI-supported virtual learning environments provide students with a more interactive and efficient teaching experience (Zhao, 2023). Research has shown that these systems are particularly effective in improving learning outcomes in fields such as mathematics and science (Kulik & Fletcher, 2016).

Disadvantages of Using Artificial Intelligence in Science Education

Despite the rapid advancements in AI, relying solely on technology in education is not ideal, as technology still contains some deficiencies in data processing and requires preparedness for unforeseen challenges (Popenici & Kerr, 2017). While AI holds promise, it faces several technological obstacles and barriers. In the context of education, these challenges become even more complex and difficult to overcome. Zhai et al. (2021) categorize the challenges AI faces in education into three main areas: technical, teacher and student-related and social ethics.

The primary technical challenge encountered in the application of AI in education is cost. Developing and implementing AI systems requires substantial investment, making high costs one of the main disadvantages of this technology. As highlighted by Nabiyev & Erümit (2022), "While AI is often discussed today, the core issue is the creation of the necessary infrastructure for its application". Education is a dynamic and continuously evolving sector, meaning frequent program changes are likely. While people typically adapt to these changes easily and at minimal cost, reprogramming computers to accommodate such shifts requires significant financial investment (Nabiyev & Erümit, 2022). This cost disadvantage not only affects schools but also students. Not every student has the financial means to purchase a laptop or access AI tools, which can result in a wider gap between students (Kurt, 2024).

Considering the significant role of human interaction in the learning process, one of the primary concerns is the low level of human-machine interaction and the inability of AI to address students' emotional needs. The lack of human interaction may lead to the deterioration of communication skills, which are critical in life. Over reliance on artificial intelligence and placing excessive trust in it is one of the potential risks (Timms, 2016). A student who can solve problems instantly with the aid of AI may lose the ability to think independently, which could negatively impact their problem solving skills. While AI provides straightforward answers without the need for discussion, a student may wish to engage in a dialogue and ask questions during human interaction. From the students' perspective, AI tools offer efficient and rapid solutions to assignments and projects. However, this may hinder deep learning, collaborative learning and creative thinking processes (EDUCAUSE, 2018). A student may become dependent on AI technologies, turning to these tools immediately upon encountering obstacles, instead of thinking critically or problem-solving on their own.

Another significant challenge awaiting the implementation of AI in education pertains to ethical issues, which concern both educational researchers and educators. A report published by the UNESCO Institute for Information Technologies in Education in 2020 highlighted the challenges associated with the use of AI in education, particularly focusing on the unequal and unfair access to information technologies across the world, leading to the digital divide (Duggan, 2020). Additionally, issues such as racism and gender discrimination have also contributed to the emergence of ethical concerns. AI, with its capacity to process big data rapidly, efficiently and effectively, has taken on critical roles in educational institutions in recent years. However, ensuring the security of students' personal data and obtaining the necessary permissions has raised significant ethical questions (EDUCAUSE, 2018). AI-based applications record information of all students who access their systems, generating algorithms based on this data. This may lead to security vulnerabilities; for instance, if intelligent computers are hacked, a significant data security breach could occur, compromising the system's integrity (Devedžic, 2004).

In addition to these fundamental issues, there are also several disadvantages associated with AI. Some researchers argue that AI applications are often designed for a general audience and therefore, fail to meet students' specific learning activities or teaching objectives, not sufficiently supporting personalized learning (Lewin, 2013; Chin et al., 2010). Another disadvantage is the risk of students encountering advertisements and distracting content in virtual environments, which can lead to attention deficits (Akdeniz, 2019). The increasing integration of technology into human life and the reduction of interpersonal interactions pose a risk of technology addiction. This situation may be detrimental to students rather than beneficial (Kengam, 2020). Virtual learning environments may lead to a decrease in students' observational skills (Öztan & Akçöltekin, 2022). AI-generated materials may also cause visual impairments and induce anxiety in students (Akdeniz, 2019). Furthermore, the misuse of AI-supported teaching programs can lead to a decline in students' social skills and critical thinking abilities (Öztan & Akçöltekin, 2022).

Artificial Intelligence Applications Used in Science Education

Artificial intelligence applications used in science education can enhance students' understanding of scientific concepts, facilitate experimentation, improve problem-solving skills and increase interest in STEM (Science, Technology, Engineering and Mathematics) fields. Some of the AI applications that can be utilized in science education include:

Simulations and Virtual Experiments

AI enables students to perform experiments in a virtual environment that they cannot perform in physical classrooms or laboratories. These applications help them better understand scientific concepts.

PhET Interactive Simulations:

This platform offers simulations in different branches of science (physics, chemistry, biology). Students experiment with these simulations, making the learning process more interactive (Moore et al., 2014).

Labster:

AI-based virtual laboratories allow students to conduct virtual experiments in areas such as chemistry, biology and physics (Dyrberg, 2016).

Personalized Learning and Adaptive Teaching

AI customizes science lessons according to students' individual needs. These applications enable students to learn more efficiently by providing content according to their pace and learning style.

Knewton:

This platform provides personalized content and recommendations based on students' achievement levels in accordance with the science curriculum (Conklin, 2016).

Smart Sparrow:

This platform analyzes students' level of understanding of science subjects and provides personalized content (Olusanya, 2023).

Automated Assessment and Feedback

In science lessons, AI automatically evaluates student responses and provides feedback. This allows teachers to focus on more students and provide guidance based on individual needs.

Gradescope:

This platform quickly assess students' written or multiple-choice exams, especially questions related to scientific concepts and calculations (Amos et al., 2021).

Socrative:

This platform automatically evaluates students' science tests and quizzes, providing quick feedback to teachers (Wash, 2014).

AI-Powered Chatbots for Science Education

AI-based chatbots answer students' questions, provide explanations and guidance in science courses.

IBM Watson Assistant:

Students can ask science-related questions to the chatbot and get a quick answer. This ensures immediate responses to students' questions, especially on complex topics (Rajeshwari & Krishna Prasad, 2020).

Woebot:

Although it is generally used for psychological support, it can also be turned into interactive chatbots that can support the learning process in science lessons (Durden et al., 2023).

Gamification and Interactive Learning Tools

AI increases students' motivation by adding gamification elements to science education. These applications help students learn science topics in an engaging and enjoyable manner.

Classcraft:

This platform gamifies science education, enhancing student interactions in the classroom. As students complete science-related tasks, they earn rewards (Nurohman et al., 2024).

Kahoot!:

Quizzes are created with questions related to science. The AI analyzes the students' performance, identifies which subjects they are struggling with and suggests additional materials (Mdlalose et al., 2022).

Virtual Reality (VR) and Augmented Reality (AR) for Science Education

AI, combined with VR and AR technologies, allows students to explore science concepts in a more realistic and immersive manner. This is particularly beneficial in subjects such as biology, physics, and chemistry, where abstract concepts are made more tangible.

Google Expeditions:

Offers virtual field trips and simulations on science topics. Makes science lessons more engaging as students make scientific discoveries around the world (Cardullo & Wang, 2022).

Merge Cube:

Through AR technology, students examine 3D science models via a physical cube, creating a more interactive learning experience (Lin, 2021).

Data Collection and Analysis Tools

In science education, AI supports the collection and analysis of data during observations and experiments.

Pasco Scientific:

Collects data through sensors during chemistry, biology and physics experiments and enables AI-based analysis on this data (Hsu & Bahrim, 2009).

LabView:

Students use this software to collect and analyze data from science experiments in various subjects (Kodosky, 2020).

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THE ROLE OF DIGITAL TOOLS IN DIFFERENTIATED SCIENCE INSTRUCTION

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Introduction

Rapidly advancing technology in the 21st century has also rapidly changed social structures. This has made it necessary for education systems to become sensitive to individual differences, student needs, and diversity. The diversity and flexibility offered by digital technologies for individual differences have positively influenced the applicability of differentiated instruction, especially in science education (Hall et al., 2003; Tomlinson, 2014).

Students' readiness levels, interests, learning styles, and needs generally differ from one another. The effective management and processing of this diversity and variety in science education depends on the flexibility and adaptability of the teaching strategies used. Digital tools enable the differentiation of teaching in many areas, from the content provided to the assessment processes (Özdemir & Yurtseven, 2023; Subban, 2006). Recent research findings reveal that differentiated instruction using digital tools positively affects students' academic achievement, motivation toward the course, and scientific process skills (Adams & Pierce, 2006; Özdemir & Yurtseven, 2023).

In this section, the theoretical foundations of differentiated instruction will be discussed, followed by an examination of how various digital tools and resources support this approach. Additionally, the roles of teachers in the use of digital tools in differentiated science instruction, the challenges encountered in the process, and future trends will be addressed to provide a comprehensive perspective on the topic.

Differentiated instruction

Differentiated instruction takes into account the individual differences of students. The teaching process, content, learning environment, and learning products are structured based on these differences (Tomlinson, 2001, 2014). This approach, whose fundamental goal is to maximize the potential of each student, is based on different theories and the integration of these theories (Gregory & Chapman, 2007).

According to Piaget's cognitive development theory, students' learning styles differ depending on their level of development (Gregory & Chapman, 2007). Vygotsky's Zone of Proximal Development (ZPD) refers to the difference between the level a student currently possesses and the level they are expected to reach. It provides a strong framework for differentiation by arguing that instruction should be slightly above the student's current level (Gregory & Chapman, 2007; Vygotsky, 1978). Gardner's theory of multiple intelligences states that each student has dominant and strong characteristics in different types of intelligence, and therefore instruction should be structured to address different types of intelligence in terms of content, process, and product (Gardner, 1999; Gregory & Chapman, 2007). Brain-based learning approaches also support differentiated instruction by highlighting that effective learning cannot occur unless students' neuropsychological needs (such as emotional safety, interest, and the search for meaning) are met (Caine & Caine, 1994; Gregory & Chapman, 2007; Jensen, 2008; Sousa, 2017). Furthermore, Kolb’s experiential learning theory explains individual differences in how knowledge is perceived and processed, recommending that instructional strategies should be adapted according to learning styles (Gregory & Chapman, 2007; Kolb, 1984).

Tomlinson (2001, 2014) defines differentiated instruction as a structured process that enables teachers to offer learning opportunities suited to students’ individual needs. In this process, teachers match the four fundamental components of instruction (content, process, product, and learning environment) with individual differences such as readiness, learning style, interests, and emotional/environmental needs. Thus, differentiated instruction evolves not merely as a method but as a student-centered educational philosophy informed by solid theoretical foundations (Gregory & Chapman, 2007).

Differentiated instruction involves planning by associating the four instructional components (content, process, product, and environment) with individual learner characteristics such as readiness level, learning style, areas of interest, and emotional/environmental needs (Tomlinson, 2001, 2014). This matching provides teachers with a comprehensive guide for planning what to teach, how to teach, how students will present their learning, and how to organize the learning environment.

- Differentiation according to readiness level is often related to "content" differentiation. Selecting different texts, materials, or experimental applications appropriate to students' current knowledge and skill levels ensures varied content (Koeze, 2007; Tomlinson, 2014).

- Differentiation according to learning styles is usually applied in the "process" dimension. Different activity paths such as drawing mind maps, conducting experiments, or engaging in discussions personalize the learning process for visual, auditory, or kinesthetic learners (Demir, 2019).

- Differentiation based on interests is particularly effective at the "product" level. Products such as posters, presentations, videos, or stories based on students' interests allow them to express their learning in a personalized context (Tadesse & Belay, 2019; Tomlinson, 2014).

- Differentiation according to emotional and environmental needs is directly associated with arranging the "learning environment". Adjustments in the physical setup of the classroom, the use of digital environments, or group work options based on students' attention spans, motivation levels, or social interaction preferences support learning (Tadesse & Belay, 2019; Tomlinson, 2014).

This systematic matching helps teachers plan differentiated instruction more effectively. Each student characteristic guides a specific instructional component, thus ensuring individualized teaching and enhancing students' motivation

Table 1. *Differentiated Instruction: Application Examples Based on Student Characteristics*

Student Characteristic	Differentiated Component	Example
Readiness	Content	Texts at varying levels, prior knowledge-based experiments
Learning Style	Process	Mind map, experiment, discussion, game
Area of Interest	Product	Poster, animation, presentation, digital story
Emotional/Environmental Needs	Learning Environment	Quiet corner, group station, digital content area, flexible seating

The differentiated instruction approach has been explicitly and systematically defined for the first time as one of the core components of the 2024 Science Curriculum (Türkiye Century Education Model) (Ministry of National Education [MoNE], 2024). In previous curricula, this approach was not directly addressed; rather, it was implicitly supported through references to individual differences (MoNE, 2013, 2018). This shift indicates that the curriculum has been restructured with a student-centered, flexible, and developmentally responsive instructional framework. Indeed, the Organisation for Economic Co-operation and Development (OECD, 2018) emphasizes that personalized instructional strategies should be prioritized in modern curricula and defines differentiation as one of the fundamental pillars of inclusive and equitable education. Similarly, the European Commission (2020) argues that, in light of the opportunities provided by digitalization and learning analytics, differentiated instruction must become an indispensable component of contemporary educational programs. In this context, the emphasis on differentiation in Turkey's new science curriculum represents not merely an educational preference but also a structural and innovative transformation aligned with global education policies.

The reflection of digital transformation on science education: The evolution of digital tools from Web 1.0 to Web 3.0

The evolution of digital technologies in education, from Web 1.0 to Web 3.0, has brought about a profound restructuring not only of tools but also of instructional approaches. During the Web 1.0 era, the internet functioned merely as a static platform for information delivery; students remained passive consumers, and teacher-centered, interaction-limited structures were reinforced (Anderson, 2007). With the development of Web 2.0 technologies, students became active participants in the learning process; beyond accessing information, production, sharing, and collaboration-based learning experiences came to the forefront (Franklin & van Harmelen, 2007; Redecker, 2009). Tools such as blogs, wikis, and social media particularly supported project-based and collaborative learning processes, enabling students to construct knowledge through multiple representations (Ajjan & Hartshorne, 2008). These developments have strengthened flexible, student-centered approaches that form the foundation of differentiated instruction (Ergül Sönmez & Çakır, 2021).

With the development of Web 3.0 technologies, advanced technologies such as artificial intelligence, augmented and virtual reality, learning analytics, and semantic networks have entered the educational environment, ushering in a new era of more personalized, diversity-sensitive digital education. With these technologies, it has become easier to plan and deliver educational content and processes tailored to students' individual characteristics, interests, needs, and readiness levels (Açıkgül Fırat & Fırat, 2021; Nasar, 2023; Popenici & Kerr, 2017). As a result, the applicability of differentiated instruction in the digital domain has increased thanks to the personalized and automated systems offered by Web 3.0 technologies.

Especially in science education, augmented and virtual reality technologies, which facilitate the understanding of abstract and complex concepts, support students' learning of concepts more easily and the retention of what they have learned through three-dimensional, interactive, and experimental learning environments (Bacca et al., 2014;

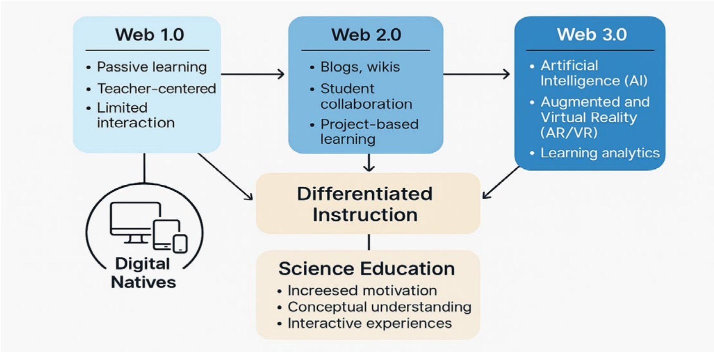
Radu, 2014; Zhang et al., 2024). Artificial intelligence-supported digital systems analyze learning data obtained from students and provide teachers with instant feedback. This makes it easier for teachers to intervene in the learning process more quickly and consciously (Holmes et al., 2019; Ifenthaler & Yau, 2020). In this respect, learning analytics not only monitor academic achievement but also track students' motivation, interests, and participation levels, enabling a more data-driven and adaptable form of teaching (Adam et al., 2018; Ifenthaler & Yau, 2020). Nevertheless, issues of data security, ethics, and privacy must be carefully addressed during this process (UNESCO, 2019).

The digital transformation has also brought about a significant shift in the student profile. "Digital natives" (Prensky, 2001) perceive technology not merely as a tool but as a natural part of life; they are capable of multitasking and are more attuned to visual and audiovisual content. Traditional teaching approaches have become insufficient for this generation, and technology-supported, gamified, project-based, and inquiry-driven instructional processes yield more effective results (Bennett et al., 2008; OECD, 2021; Selwyn, 2009). In this context, differentiated instruction not only addresses individual differences but also aligns with the learning tendencies of digital natives. Through technology integration, learning processes become more flexible, accessible, and student-centered, while it becomes imperative for teachers to develop their digital teaching competencies (Green & Hannon, 2007; Thomas, 2011).

The SAMR model developed by Puentedura (2013) provides a useful framework for explaining this digital evolution at the instructional level. The SAMR model categorizes the integration of digital technologies into teaching processes into four levels: Substitution, Augmentation, Modification, and Redefinition. For example, in science education, modeling a concept with a digital simulation instead of simply presenting visuals (Substitution), making the simulation interactive (Augmentation), enabling students to produce new content using digital tools (Modification), and creating entirely original digital experiences that were previously impossible (Redefinition) allow the teaching process to be differentiated in multiple dimensions. This enables teachers to effectively use technology not only to deliver learning content but also to restructure and differentiate learning processes (Kilbane & Milman, 2024).

In conclusion, the transition from Web 1.0 to Web 3.0 has created theoretical and structural development and transformation. Digital technologies have provided students with educational opportunities that are sensitive to their individual differences, interests, and needs. In the context of science education, differentiated instruction supported by these technologies has increased students' conceptual understanding and motivation levels (Lamb et al., 2023; Marsh, 2022; Wu et al., 2019).

Figure 1. *Digital Transformation and Differentiated Instruction in Science Education: From Web 1.0 to Web 3.0*



Teaching with digital tools in differentiated science instruction

Simulations and modeling software, augmented and virtual reality applications, interactive digital laboratories, mobile applications, game-based digital tools, learning management systems (LMS), and artificial intelligence-based applications are technologies that are frequently used at various levels from elementary school to university in science education today and play an important role in the implementation of differentiated instruction. The following sections discuss the roles of these digital tool technologies in providing learning experiences tailored to the diverse needs and characteristics of students in science education.

Simulation and modeling software in differentiated science instruction

Computer-based simulation and modeling software visualizes abstract concepts in science education and provides interactive learning environments. This allows students to learn at their own pace (Rutten et al., 2012). For example, simulations such as PhET and Gizmos provide students with virtual yet interactive and safe opportunities to conduct experiments repeatedly on various science and mathematics topics (Finkelstein et al., 2005; Smetana & Bell, 2012). These tools allow teachers to easily adapt materials for different learner groups. Indeed, online interactive simulations can be tailored for students with special educational needs, advanced learners, or those facing language barriers (Papastergiou, 2009). Because simulations offer students the opportunity to learn through trial and error, those requiring more practice can repeat the experiences multiple times, while faster learners can progress independently, facilitating the management of learning pace diversity within the classroom (Olympiou & Zacharia, 2012).

Moreover, simulation software is highly effective for differentiating content and adapting instructional processes. For example, a teacher can design simulation-based activities at varying levels of difficulty: a more guided discovery activity for basic learners and a more open-ended exploration for advanced learners (De Jong et al., 2013). Platforms like ExploreLearning Gizmos promote inquiry-based learning by offering interactive cases and experiments that can be modified to suit the needs of individual students (Pannizzo, 2022). At the middle school level, a standard science-mathematics simulation can be adapted for students with learning difficulties by simplifying the interface, adding extra instructions, and providing engaging contextual examples (Khan, 2011). Similarly, by using simpler language, simplifying the content, and making it more concrete, a science simulation can be adapted to the elementary school level (Rayan et al., 2007). In conclusion, simulation and modeling tools can be used to tailor science topics to different student characteristics, thereby differentiating instruction. Additionally, these software tools enable the same concept to be taught at elementary, middle, high school, and higher education levels with varying levels of complexity and depth (Zacharia & Olympiou, 2011).

Augmented and virtual reality applications in differentiated science instruction

Augmented reality (AR) and virtual reality (VR) technologies make abstract concepts in science education more concrete, making students' learning more meaningful and deepening their understanding. VR transports students into a completely virtual environment, while AR enriches the real world with digital elements. Both technologies offer interactive learning environments that cater to different learning styles (Bacca et al., 2014; Radu, 2014). For example, a student who learns better visually can explore planets in a three-dimensional and interactive environment using VR glasses or examine a model of the Solar System using AR technology to understand the subject more easily (Howard & Davis, 2023). Research shows that AR technologies are sensitive to different student characteristics, thereby offering personalized learning experiences (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). Timur and colleagues (2019) reported in their study that sixth-grade students learned the topic of cells more easily at their own pace through AR-supported activities, that these activities enriched the learning process, and that they positively changed students' attitudes toward the lesson. Similar studies conducted with gifted students also emphasize that AR technologies deepen conceptual understanding by offering differentiated learning experiences that take into account individual differences and needs (Coştu, 2024; Önal & Önal, 2021).

AR and VR applications can be effectively used at every level of education, from elementary school to higher education. Elementary school students can examine the human body and organs in three dimensions and interactively using AR cards. Middle school students can perform chemical experiments in a safe environment without risk using VR laboratory simulations. Medical students can easily analyze the complex structures of the human body using these technologies (Merchant et al., 2014). All these examples demonstrate that AR/VR technologies effectively support differentiated instruction in science education by adapting content to the level of the learners and diversifying learning pathways.

Interactive digital laboratories in differentiated science instruction

Real-world laboratory experiences are an indispensable component of science education. However, it is not always possible for all students to participate in laboratory work simultaneously and at the same level. Virtual laboratory environments and interactive digital experiment platforms provide students with the opportunity to conduct experiments at their own pace in a safe environment. For example, digital platforms like LabXchange create a personalized learning environment. Students can learn from their own mistakes, repeat experiments, and conduct independent research throughout the process (Dyrberg et al., 2016; LabXchange, 2023; Tatlı & Ayas, 2010). Digital experiment environments with flexible structures facilitate learning, especially for students at various readiness levels. The content of an experiment at the middle school level can remain simple with different difficulty levels; however, the same content can be deepened with much more complex scenarios at the high school level or higher. This structure contributes to the provision of learning experiences tailored to different learner characteristics (Wu et al., 2019). Furthermore, virtual laboratories provide the same experience to all students regardless of a school's physical equipment and available materials. Conducting dangerous or costly experiments in a virtual environment enhances safety and ensures the continuity of studies (Rutten et al., 2012).

Various studies have shown that virtual laboratory applications have positive effects on science learning outcomes and contribute to the learning process by enabling students to participate in experimental activities at their own learning pace (De Jong et al., 2013). For example, in a study conducted with two groups of students with different prior knowledge levels, students conducted experiments in a virtual chemistry laboratory using differentiated instruction tailored to their individual learning needs. During this process, students were presented with content at different levels of difficulty. The research results revealed that differentiated instruction, planned based on students' individual needs and readiness, made the teaching process more efficient (Wu et al., 2019).

Mobile applications and gamification tools in differentiated science instruction

Mobile applications and game-based digital tools contribute to differentiated instruction by offering learners customized learning paths. These tools cater to students' different learning characteristics in science education through various applications such as animation, sound, augmented reality, and virtual experiments. The learning process can be structured according to individual characteristics through gamified tasks, feedback, and hints (Marsh, 2022; Nuanmeesri, 2019). Additionally, students can continue learning independently of the classroom with such applications. In other words, they can take the learning environment outside the classroom. For example, using a mobile application on their phones, they can collect different data in different environments by using their phones as a measuring device (Bogusevschi et al., 2020).

Game-based applications such as Kahoot!, Quizizz, and Classcraft prepare step-by-step content based on students' individual characteristics and design exams and tasks with different levels of difficulty (Mcglynn & Kelly, 2020). In these applications, students take exams appropriate to their level and progress at their own pace according to learning objectives created based on their readiness and prior knowledge. A student with a low level of readiness focuses on a goal that is appropriate for them, while a student with more prior knowledge focuses on a higher goal. Teachers can prepare tiered assessments categorized as "normal," "challenging," and "very challenging," ensuring that each student experiences success at an appropriate point in their learning journey. Thus, the personalized goals and freedom of choice offered by gamification enable different learning paths to emerge, thereby supporting differentiated learning environments (Bouchrika et al., 2021; Marsh, 2022).

In conclusion, mobile applications and game-based applications reflect the nature of differentiated instruction by structuring the learning process according to the student's interests, readiness, and learning style (Hall et al., 2003; Tomlinson, 2014).

Learning management systems (LMS) in differentiated science instruction

Learning Management Systems (LMS) can be used to provide differentiated instruction in science classes. Through systems such as Moodle, Google Classroom, or Canvas, processes such as content distribution, assignment and exam management, discussion forums, and progress tracking can be carried out. Teachers can use these platforms to assign different content, tasks, and exams to different student groups with varying abilities. They can give each student different assignments or research projects. For example, while teaching the same topic, a teacher can provide some students with exercises to reinforce the topic, while assigning more advanced students tasks that require them to conduct research on the same topic and challenge their critical thinking skills. Thus, all students follow a learning pathway suited to their levels and needs. Another advantage of LMS environments is that they offer flexibility in terms of time and space. Students can access online content whenever they wish and learn at their own pace; a fast learner can access more advanced materials, while a student needing additional support can be given supplementary resources and extended time (Burgstrom, 2017; Jamaluddin et al., 2022; Palahicky, 2015). By using a learning management system, it is also possible to provide students with choices over their learning schedules — such as when and in what order to study topics — thus offering a flexible learning experience that aligns with their individual needs (Chen & Wang, 2021). This flexibility makes it possible to create a digital environment tailored to each student's learning style. This supports the student-centered structure of differentiated instruction.

When used in conjunction with learning analytics tools, LMS platforms provide teachers with important insights about their students. The system regularly monitors student participation in activities, quiz results, and assignments. This allows teachers to easily identify areas where students are struggling and plan additional work. Similarly, students who grasp the material quickly are supported with projects and assignments that allow them to explore the topic in greater depth. It enriches teaching. In short, these systems help teachers get to know their students better and quickly adapt their lessons to their needs (Adam et al., 2018; Ismail et al., 2021; Mwalumbwe & Mtebe 2017).

Artificial intelligence-supported systems in differentiated science instruction

One of the main goals of differentiated instruction is to create learning environments that are tailored to student differences. Today, artificial intelligence-based technologies have made it easier to achieve this goal (Holmes et al., 2021; Lamb et al., 2023). Thanks to artificial intelligence-supported systems, various data such as students' previous achievement levels, learning speeds, and areas of interest can be analyzed, and personalized content and tasks can be defined for students. With such systems, students are provided with instant feedback, contributing to their ability to better manage their own learning processes (Herliana et al., 2024). For example, an AI-supported education platform can offer more challenging and complex tasks to students who grasp the subject quickly, while recommending content that helps other students who are struggling with the same subject to learn and repeat it in a meaningful way.

Traditional learning management systems (LMS) are platforms where the teaching process is guided by the teacher and many tasks are performed by the teacher. AI-based systems, on the other hand, can automatically analyze student data and adapt the learning process accordingly. This reduces the teacher's workload and provides a more flexible and data-driven learning environment (Alotaibi, 2024; ELearning Industry, 2024). The integration of such systems into education holds the potential to enhance student achievement by supporting personalized learning experiences (Alotaibi, 2024; Ruslim & Khalid, 2024).

Table 2. *Classification of Digital Tools Supporting Differentiated Instruction in Science Education*

Category	Differentiation Strategy	Example Tools
Simulation & Modeling	Tailored simulations make abstract concepts concrete.	PhET, Gizmos
Interactive Digital Labs	Self-paced experiments meet individual needs.	Labster, LabXchange
AR/VR	Visual-auditory content engages diverse learners.	Merge Cube, CoSpaces
Mobile Apps & Gamification	Tasks and levels adapt to interests and pace.	Kahoot!, Quizizz
LMS	Teachers assign differentiated content and assessments.	Moodle, Google Classroom
AI-Supported Systems	Content and feedback are personalized via real-time data.	Khanmigo, Century Tech

Strategies for supporting differentiation through digital tools

Differentiating content

Teachers can differentiate content by presenting the same science topic in various digital formats according to students' needs and learning preferences. For example, basic-level students can learn about the states of matter (solid, liquid, gas) through daily-life examples, visually-supported activities, and animations. Intermediate students can explore phase changes (melting, freezing, evaporation) using simple experiments and interactive simulations. Advanced students, on the other hand, can investigate the effects of temperature changes on phase transitions through augmented reality applications, designing their own small-scale experiments and interpreting the results. This variety enables students to grasp the topic at their own pace and level (Kilbane & Milman, 2014).

Differentiating process

Digital platforms allow the design of tasks, projects, and online group activities adapted to students' interests and proficiency levels. For example, one group of students may engage in a virtual laboratory activity (LabXchange), while another group works on the same topic via a virtual discussion panel (such as Padlet or Jamboard). Interactive quiz tools like Kahoot can group students based on response times and accuracy, offering higher-order cognitive questions to advanced students and reinforcement activities to others. This flexibility facilitates providing personalized learning experiences to every student.

Differentiating product

Students are given opportunities to express what they have learned in various digital formats. They can demonstrate their knowledge and skills through digital storytelling (StoryJumper), e-posters (Canva), video presentations (Adobe Express), or animations (Powtoon). This approach supports student autonomy and fosters creative products that cater to different types of intelligences (Gregory & Chapman, 2007).

Differentiating learning environment

Thanks to virtual environments, augmented reality applications, mobile learning tools, and online work platforms, students can continue learning wherever and whenever they want. This both supports individual learning paces and personalizes learning spaces. For instance, while studying the "life cycle of plants" in a science class, one group of students can observe plant growth step-by-step using PhET simulations on classroom computers. Simultaneously, another group can explore real plants using an AR-supported mobile app (e.g., Plantale) in the school garden. Allowing students to choose their own learning environment increases their interest and positively affects their participation in class (Patall et al., 2010).

Digitalization and differentiated instruction in science education: Teacher roles, challenges, and future trends

The use of digital technologies in science lessons has changed not only the way topics are taught but also the overall structure of teaching. Instead of teacher-centered methods, more flexible learning methods structured according to students' individual needs using digital tools are now preferred (Ravitz et al., 2000). This has facilitated the adaptation of differentiated instruction to science education. However, simply knowing how to use technology is not enough. Teachers must have a thorough understanding of the subject matter and select the most appropriate digital tools to make their lessons effective and meaningful (Mishra & Koehler, 2006). For example, when teaching the topic of "States of Matter" in elementary school, augmented reality technology can be used to visually demonstrate the melting and vaporization of ice for some students. For other students, different methods such as interactive simulations or digital stories may be preferred. However, in order to provide this variety, it is not enough for the teacher to be familiar with the technology; they must also have a good understanding of the students' needs and the structure of the subject matter.

Today, digital technologies are frequently used in educational settings. However, this situation also brings some challenges. In differentiated instruction, teachers need to have both technological and pedagogical knowledge to prepare content and activities tailored to the individual needs of students (Ertmer et al., 2012). On the other hand, some schools have infrastructure deficiencies or problems such as internet access. For this reason, not all students may be able to benefit equally from these opportunities (OECD, 2023). Another risk is the development of excessive dependence on technology. Research shows that spending long hours in front of a screen can lead to attention deficits, learning difficulties, and loss of motivation in students (Kuss & Griffiths, 2017; Selwyn, 2016). Conducting science lessons entirely using digital tools may reduce students' opportunities for direct experience, which can negatively affect the development of scientific process skills (Çamalan & Demirbaş, 2024; Ünlü, 2019). Therefore, the use of digital tools should be considered part of a balanced learning design, with technology seen as a means rather than an end.

Future trends suggest that digital technologies in science education will further evolve to offer increasingly personalized learning pathways. AI-supported systems analyze student data to recommend individualized content and tasks, providing teachers with more efficient ways to plan differentiated instruction (Kotsis, 2024; Sun et al., 2025). Augmented reality and virtual reality applications transform abstract concepts into three-dimensional experiences that students can directly engage with, making learning more concrete and lasting (Bacca et al., 2014; Radu, 2014). However, for these technologies to be effectively incorporated into educational processes, continuous professional development for teachers and the purposeful selection of digital content are critical (Marsh, 2022). Education systems are also encouraged to invest in infrastructure that reduces digital inequalities and to expand the focus on technology-supported differentiated instruction in teacher preparation programs. In doing so, it will be possible to create learning environments that support individualized, interactive, and deep learning experiences in science education.

As outlined in this section, digital tools are not merely elements of innovation in science education; they are essential components that make the real implementation of differentiated instruction possible. Differentiated instruction has become not a choice but a necessity for effective science education in today's world. Ignoring differences in students' readiness levels, learning styles, and individual interests creates a learning environment that is contrary to the nature of science itself. Therefore, science education must adopt approaches that are flexible, production-oriented, and student-centered. Digital technologies serve as powerful tools that enhance the applicability of differentiated instruction and offer new learning pathways that deepen students' scientific understanding (Howard & Davis, 2023; Smetana & Bell, 2012; Tomlinson, 2014). Solutions such as simulations, augmented reality applications, online laboratories, and AI-supported systems have the potential to transform student diversity from a challenge into an opportunity. However, effectively realizing this potential depends on teachers who design technology-supported instruction not merely as a means of presentation but as a process that personalizes learning and fosters production-based activities (Dixon, 2014). Differentiated science instruction supported by digital technologies will become effective and meaningful only under the guidance of teachers who use technology consciously, design student-centered learning processes, and adapt instruction according to the individual characteristics of their students.

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THE USE OF METAVERSE IN EDUCATION

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Introduction

Today, with the advancement of technology, the importance of distance education is increasing. Distance education platforms include technologies that enable teachers and students to carry out learning activities without time and space constraints (AlArimi, 2014). These technologies include television broadcasts, printed or online educational materials, video and audio recordings, interactive live lessons (Sözen, 2020). Due to these characteristics, numerous educational institutions have provided distance learning options for students unable to engage in in-person education. Additionally, establishments like Open University, which exclusively serve students through distance education, have been founded (Yıldırım, 2012).

Distance learning is becoming more widespread in Turkey every day, in line with global developments. Distance education activities began in the 1950s and entered a significant development phase in our country in the 2000s. This situation has led to distance learning programs offered by the public and private sectors being widely preferred by students. At the same time, this situation shows that education in the country is accessible to everyone.

In the context of the Covid-19 crisis and the stay-at-home periods all over the world, interest in the remote work and distance education and online 3D digital content has increased dramatically. In this transformation, a lot of industry like education, economy, trade and health services has also moved towards the technology innovations, and most of the businesses and deals are being carried out online. The study of Park and Kim (2022), have concluded that the containment measures to alleviate Covid-19 propagation, in personal activities, have been a fundamental factor for the fast dissemination and use of technology and tech alternation by users. Due to the pandemic, the transition and adaptation of individuals to the digital world has accelerated (Kang, 2021). This digital transformation process has also triggered developments in the Metaverse. Distance education in Türkiye has been realized through three television channels and the Education Information Network (EBA) (MoNE, 2020). In addition to these platforms, various distance education methods such as video conferencing, virtual classroom applications, video sharing and written materials are also used (Can, 2020). Teachers, especially those planning the distance education process, have stated that they do not have sufficient command of the materials they can use in these environments (Mayasari & Kemal, 2020). Teachers stated that they had difficulty in creating a rich classroom environment with interesting materials that would ensure the active participation of students (Demirtaş & Kavuk, 2021). As can be seen, the teachers could not plan the distance education process sufficiently, yet they tried to provide education to the students. The lack of communication and interaction in distance education has increased the importance of the Metaverse and it has become a technology that supports distance education (Zi & Cong, 2024).

The Metaverse is a multi-user digital universe similar to the real world. Metaverse, which combines physical reality and virtual environments, is a reflection of applications such as image, audio, video, 3D objects, augmented and virtual reality and activates multiple senses (Lee et al., 2022). It is a type of online community where users can interact, create objects and design environments and activities (Altunal, 2022). The metaverse is a virtual environment where users come together to engage in activities such as working, shopping, attending classes, pursuing hobbies, and participating in social gatherings by creating avatars that represent themselves (Wiederhold, 2022).

The metaverse is a low-cost environment for applied learning environments where there is less risk and fewer physical inequalities (race, color, gender, physical disability, etc.) in the avatars that identify users (Kalkan, 2021; Duan et al., 2021). Also, the metaverse makes learning more engaging through interaction with avatars and objects (Calvert & Abadia, 2020). Researchers define Metaverse as web-based communication environments that support school-based teaching and learning interactions (Alali & Wardat, 2024). Such interactions increase the intention to use Metaverse technology in education (Wong et al., 2024).

Metaverse studies have started in the international literature since the 2000s, with the first academic studies focusing on design dimensions (Jaynes et al., 2005) and economic and socio-political contexts (Papagiannidis, Bourlakis & Li, 2008). In the following years, both nationally and internationally, metaverse studies have accelerated in science and technology fields such as architecture and engineering. The metaverse, which is designed as a simulation of the real world and covers almost all areas related to human beings and society, has attracted the attention of social sciences over time, and the formation of academic products in many fields such as religion, literature, art and education has not been delayed (Narin, 2021). International metaverse studies in the field of education, although quantitatively less, mostly focus on topics such as hybrid education (Almarzouqi et al., 2022; Diaz et al., 2020), student-centered learning (Suh and Ahn, 2022), classroom metaverse applications (Fu and Pan, 2022; Lopez-Belmonte et al., 2022; Wang and Lai, 2023), project-based learning (Arbogast, 2019; Jarmon et al., 2008). Similarly, metaverse studies in the field of education in Türkiye are mostly on augmented reality applications (Akkuş & Özhan, 2017; Uzunhazneci, 2019), design-based learning (Altunal, 2022), language teaching (Can, 2012; Demirbağ, 2022; İliç, 2013), and the effect of virtual environments on learning (Karadayı, 2022; Özonur, et al., 2016; Tepe, 2019). In short, it is obvious that metaverse studies, which are mostly concentrated in fields such as architecture and engineering in the general context and mostly in the instructional dimension in the educational context, have not yet gained a comprehensive place in the field of educational administration.

The use of the metaverse in science education attracts students' interest and places them in an immersive learning environment. In this environment, students have the opportunity to design experiments collaboratively and carry out the experiments they have designed. However, there are some limitations and challenges regarding the use of the metaverse in education. One such challenge is that students may have difficulty focusing on the lesson when participating in the learning environment remotely (Taş and Bolat, 2022; Park and Kim, 2022). At the same time, it is believed that technical problems such as the quality of the internet connection or glitches in the virtual environment can negatively affect students' learning experiences. The use of the metaverse in education also brings with it privacy and security issues (Wang, et al., 2022). Bibliometric studies (Ji et al., 2022) and studies investigating innovative strategies using virtual reality and artificial intelligence (Brzezinski and Krzeminska, 2023) are being conducted to examine these issues. At the same time, researchers continue to work on solutions to the problems encountered in the use of the metaverse in education today.

Metaverse concept

The concept of metaverse, which is formed by combining the concepts of "meta" (beyond) and "universe," is defined as a digital environment where individuals can interact with avatars within a virtual universe and design various activities as a result of this interaction (Park & Kim, 2022; Suh & Ahn, 2022). This concept is not just a technology or a platform; it is also a new dimension of digital sociality, economy and learning. The metaverse, which gained popularity with Facebook's rebranding as "Meta" in 2021, is now signaling potential transformations in many areas, especially education.

The concept of the Metaverse dates back to 1974. The concept of the Metaverse was first discussed in Neal Stephenson's science fiction novel Snow Crash in 1992 (Maharg & Owen, 2007; Sachs, 2021). Later, in the novel Ready Player One, a Metaverse area called OASIS was mentioned (Sparkes, 2021). With the development of the use of computers, the development of the Metaverse accelerated. Between 1992 and 2016, the era of virtual worlds and multiplayer online gaming platforms began for the Metaverse (Lee et al., 2022). Active World, Online Traveler, Second Life and Minecraft, which were released between 1995 and 2011, respectively, led to the development of the multiplayer virtual world era. The first uses of the Metaverse in education began in the early 2000s with virtual worlds such as Second Life. Then, thanks to VR/AR technologies, more realistic, interactive learning environments were created. After the pandemic, the use of the metaverse has become widespread, and most educational institutions (universities, high schools, etc.) have started offering metaverse-based education.

Compared to traditional education, education in the metaverse offers more engaging, interactive, and accessible learning experiences (Soni & Kaur, 2023). Metaverse offers a variety of rich educational opportunities, including virtual classrooms, virtual field trips, simulations, collaborative projects, and shared learning. In this environment, students and teachers can interact through avatars, can be easily accessed from different parts of the world, and learning experiences become more immersive compared to physical classrooms. Traditional education, on the other hand, involves face-to-face interaction in physical classrooms and generally more passive learning methods. As a result, the Metaverse has the potential to revolutionize education by providing dynamic and customizable educational experiences (Soni & Kaur, 2023). Overall, the potential of the Metaverse in education offers a more immersive, personalized, and interactive learning experience that is not possible with traditional e-learning.

Considering that the metaverse will be among the different teaching methods that will emerge with advancing technology, it is clear that science courses will be the most suitable type of course for teaching abstract, micro, and macro concepts, which are the most challenging for students (Hwang and Chien, 2022). In this context, considering its close relationship with the disciplines of physics, biology, and chemistry, the implementation of metaverse applications in schools is of great importance (Bibri, 2022). The following conditions must be met in the metaverse environment to be prepared for science education (Suh and Ahn, 2022):

1. Designing an environment that is appropriate for the aims and objectives of the course program,

2. Defining all concepts covered in the course topics in the prepared environment,

3. Being appropriate for educational processes such as prior knowledge, introduction, scope of the topic, development, and measurement-evaluation,

4. Ensuring that laboratory and observation opportunities are compatible with daily life,

5. Not causing conceptual misconceptions (supernaturalism, teleportation, scientific misconceptions),

6. Being ethical.

In science education, metaverse-supported teaching can contribute to the future of the country in terms of technology and pedagogy. In order for developing countries to come to the fore in the technological revolution, they need to effectively use innovative technology in education for educational purposes. One of the platforms where we can use innovative technology in education today is the metaverse application. This application provides the closest interaction between teachers and students in real life. Within the scope of science education, the use of augmented reality, virtual reality, and mixed reality technologies for educational purposes through individuals' real avatars will contribute significantly to the construction of a technology-adopting society in the coming periods.

In conclusion, the concept of metaverse has the potential to offer revolutionary innovations in the world of education. However, realizing this potential is possible not only with technological investments but also by considering ethical, pedagogical and social dimensions.

Technologies on which the metaverse is based: virtual reality, augmented reality, mixed reality and extended reality concepts (VR/AR/MR/XR)

Virtual reality

Virtual reality is a technology that allows students to experience a virtual world using computer simulation systems, allowing them to move interactively within a virtual world through simulated environments created by computers (Yu, 2021). Thanks to the combination of real-life data and electrical signals generated by computer technologies, this technology allows people to feel virtual worlds so realistically that they cannot distinguish them from real life (Calvert & Abadia, 2020). Computer graphics, artificial intelligence, modern multimedia, sensors, pattern recognition and other technologies are used extensively in virtual reality to simulate individuals' auditory senses, visual comprehension, tactile senses and other similar senses through real-life-like environments (Sivunen & Nordbäck, 2015).

The rapid development and advancement of technology has significantly impacted the education system, offering different tools to students. In this revolutionary process, tools such as virtual reality (VR) also play an important role (Khodabandeh, 2022). Today, virtual reality technology is becoming a new educational tool to improve students' education. Virtual reality technology helps students to better understand information and grasp basic concepts more effectively in a safe learning environment (Broekens et al., 2012). Virtual reality technologies are increasingly widely used in education. This technology helps to reduce the uncertainty and confusion students face in the learning process by strengthening the process of constructing knowledge (Broekens et al., 2012; Hamilton et al., 2021; Marks & Tomas, 2022).

In science education, it is well known that students need interactive and research-based learning experiences. Virtual reality meets these needs by enabling students to interactively learn about difficult and seemingly impossible science concepts through three-dimensional simulations (Shin, 2003). These virtual environments offer students the opportunity to enrich their learning processes. At the same time, they provide opportunities for data collection and learning from mistakes related to science issues.

Virtual reality programs are used as an effective experimental tool in science classes (Bayraktar and Kaleli, 2007). Such virtual reality applications ensure the effective use of technology in education. The integration of virtual reality technology into science lessons increases students' motivation to learn and enables high-quality learning in teaching processes (Çavaş et al., 2004). Indeed, Kocaçavuş and Cerit (2023) investigated changes in the academic achievement of fourth-grade students in science classes through the use of virtual reality glasses. The study found that virtual reality glasses improved academic performance; it also observed an increase in students' curiosity and motivation toward the course.

Augmented reality

Augmented reality is defined as an augmented real world where virtual data is added to the real world in real time directly or indirectly with computers (Billinghurst et al., 2001). It combines the real world and the virtual world interactively, acting as a mediator in the user's direct interaction with them (Schmalstieg & Höllerer, 2016). Augmented reality mediates the interaction of users not only with virtual environments but also with the augmented reality environment of the physical real world augmented with virtual objects (Billinghurst et al., 2001; Schmalstieg & Höllerer, 2016; Porter & Heppelmann, 2017). As a result of the intertwining of the computer world and the physical world, pushing the limits of imagination, a new era has begun with technologies such as augmented reality. The new generation virtual world that hosts the virtual world and the real world is characterized as augmented reality (Danielsson et al. 2020).

Today, augmented reality applications that can be easily used with the help of computers, tablets and smart phones have become widespread in all areas of life. For this reason, augmented reality technologies have started to offer people a different perspective and a new experience. Augmented reality environments are created by adding virtual objects to real world images (Gorman & Gustafsson, 2020). Augmented reality is based on two technologies: video-based and optical-based. In video-based technology, scenes integrated with the real world are seen on computers, tablets and smartphones, while in optical-based technology, they are seen with the help of glasses (Porter & Heppelmann, 2017). Canadian Steve Mann's eyewear prototype "Eye Tap", which is the basis of today's augmented reality glasses, was developed in 1980, and the glasses, which have an elegant, ergonomic and stylish appearance, can also record and transmit images with the help of the camera on it (Mann et al., 2005).

The increasing demand for more engaging learning environments and the enhancement of educational quality and effectiveness has prompted educators to reassess fundamental principles and integrate new technologies into learning spaces (Kellner, 2002). The generational shifts among learners, who are pivotal to the learning process, have significantly influenced changes within the educational system. Currently, learners identified as Generation Z exhibit a higher proficiency in technology compared to their predecessors, enabling them to access information more rapidly through technological means (Prensky, 2001). This cohort is deeply connected to technology and digital gaming, expressing a desire for similar interactive experiences within educational settings, thereby underscoring the necessity for course materials that leverage new technologies to be made available to them (Bulun et al., 2004).

Augmented Reality technology is widely used in disciplines such as physics, chemistry, and biology, as well as geometry, mathematics, and astronomy.

Augmented reality technology, which plays an important role in science education, allows students to observe without the need for a laboratory environment by creating a virtual environment. This makes education more efficient.

Educational benefits provided by AR (Augmented Reality) (Önder, 2016):

- Makes abstract concepts concrete.
- Contributes to a better understanding of concepts.
- Facilitates comprehension by presenting information visually.
- Makes the learning process more enjoyable for students.
- Captures students' attention and increases their motivation.
- Supports students' information processing.
- Provides visual-spatial information related to the real world.

It is predicted that augmented reality (AR), an innovative and interesting technology, will be appealing to both teachers and students when used in education. This technology, which appeals to multiple senses, is considered an effective tool for creating rich educational environments necessary for learning to take place (Luckin & Fraser, 2011).

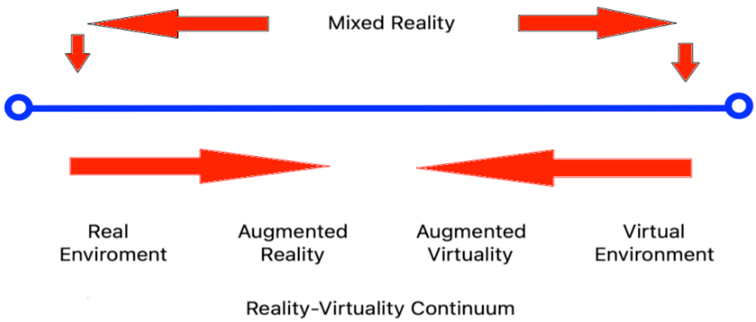
Mixed reality

Mixed reality, a reality technology that is a mixture of virtual reality and augmented reality, is a type of virtual reality and is a broader concept than augmented reality that enriches the real world with synthetic data (Tamura et al., 2001). Mixed reality technology, which emerged after augmented reality and virtual reality technologies, can be characterized as an enhanced augmented reality experience. The difference from augmented reality is that virtual objects in real environments are positioned like real objects and this positioning is realized by aligning with real objects in real time (Avcı & Taşdemir, 2019). In other words, virtual objects are not only superimposed on the real world, but can also interact with the real world continuously (Doğan et al., 2021). In mixed reality technology, real and virtual data are combined in the same environment, increasing the reality of virtual data and transforming the existing real environment into an environment where virtual data can be used (Türksoy & Karabulut, 2020). It can be stated that transformations also shape the way reality is perceived.

In mixed reality, unlike virtual reality, users are not cut off from the real world and can communicate instantly with layers created on reality, as in augmented reality technology. In this technology, users can be offered a more realistic and unlimited experience (Papuççiyan, 2021). In summary, with mixed reality, users can communicate with physical and virtual objects in real time, offering a realistic experience away from artificial virtual reality. Mixed reality technology can involve a number of processes such as seeing with a Head Mounted Display (HMD) headset, Leap Motion device, bluetooth connected gesture controllers, data gloves or simply touching holographic images with the hand. According to Yengi and Bayrak (2018), mixed reality includes technology in which virtual objects can interact with real objects. In this way, the user can associate the real living space with virtual objects with full participation.

The first use of the concept of mixed reality was in the article titled "Classification of Mixed Reality Visualizations" published by Milgram and Kishino in 1994. The concept of mixed reality is conveyed with the virtuality process diagram as seen in Figure 1. The mixed reality universe included the concepts of real environment, virtual environment, augmented virtuality and augmented reality.

Figure 1. *Simplified Virtuality Process Demonstration*



According to the representation in Figure 1, the right side represents the virtual environment consisting of virtual objects and the left side represents the real environment. In this context, mixed reality can be defined as the coexistence of virtual and real objects on a single screen between two points in the virtualization process. In this regard, it can be stated that mixed reality covers the part between the real environment and the virtual environment. The difference of mixed reality technology from virtual reality is the movement space and the concept of space it provides to the user. As a matter of fact, in a mixed reality environment, the user can experience the virtual environment created in the physical world without leaving the place where they are located with only the HMD headset.

The use of MR technologies in science education helps students learn abstract scientific concepts in a more concrete way. MR applications make students' learning processes more interactive and interesting. Mixed reality technology finds application across various domains. One such domain includes museums and historical sites. In a study conducted by Diker (2019), the focus was placed on the analysis of the Troy Museum utilizing mixed reality technology. The research involved the examination and comparison of museums from diverse regions globally. Furthermore, the study explored the methodologies for implementing mixed reality technology within museum settings. The findings indicated that the Troy Museum possesses a framework conducive to mixed reality applications.

Studies have shown that students achieve higher academic performance in environments using mixed reality technology compared to traditional teaching methods. At the same time, it has been determined that MR applications increase student motivation (Zhang et al., 2022). Indeed, Beyoğlu, Hürşen, and Nasiboğlu (2020) used mixed reality applications to teach science to elementary school students in their studies. The research found that students' motivation for collaborative work increased. At the same time, as a result of interviews conducted with students, they stated that mixed reality should be used in all courses and that there was an increase in their motivation to learn science after the application.

Extended reality

Augmented Reality refers to applications that aim to integrate the physical world with the virtual world in real time within the same frame (Özarslan, 2011). The most important feature of augmented reality is that it expands the user's view of the physical world through virtually created objects. Based on numerous studies conducted in this field (Barfield, Craig, and Wouter, 1995; Milgram, Takemura, Utsumi, and Fumio, 1994; Rolland, Holloway, and Fuchs, 1994), Azuma (1997) argued that such a system should have three basic features in order to prevent augmented reality from being reduced to certain technologies: (1) combining the real and the virtual, (2) real-time interaction, and (3) three-dimensional positioning in space. In this case, virtual reality involves creating an artificial environment in which the individual is completely or partially isolated, while augmented reality involves enriching the environment of the world in which the individual exists with elements created through a process involving certain references.

Extended reality (XR) refers to virtual reality, augmented reality, and mixed reality, which are created using computers and have a wide range of applications today, including military, healthcare, gaming, education, teaching, and design visualization. Augmented reality is defined as an umbrella concept that encompasses interactive types of reality with a high level of immersion and a sense of presence, created either entirely virtually or by blending the virtual and real worlds (Özarslan, 2013).

Augmented reality applications involve taking information from real environments via cameras, imaging devices, or various sensors, processing it, and then combining it with computer-generated elements to create a software-based representation of the real world. These elements created on a computer can be multimedia content such as text, 2D or 3D images/objects, sounds, images, animations, simulations, or they can consist of enhancements that present these elements interactively. As a result of these elements created by computers, it is possible to create environments of superior quality that allow us to interact in real time at a level close to reality.

The first application of augmented reality in education was used in 1992 by Tom Caudell to assist in the training of workers at Boeing (Caudell and Mizell, 1992). In 2009, Maier, Klinker, and Tonnis developed an augmented reality application called "Augmented Chemical Reactions" to support the teaching of chemical reactions in chemistry classes. They stated that this system made it easier for students to understand the process and reduced their fear of chemistry classes (Maier, Klinker, & Tonnis, 2009). Özarslan (2013) investigated the effect of using augmented reality-enriched learning materials on learners' success and satisfaction levels. The research concluded that there was a positive increase in students' academic achievement and satisfaction levels. Similarly, the use of augmented reality-enriched learning materials has been shown to have a positive effect on learner achievement in this study, as in various studies (Hsiao and Rashvand, 2011; Kaufmann and Schmalstieg, 2002; Gutierrez et al., 2010; Slijepcevic, 2011) conducted in the field.

Extended reality in education will add a new dimension to learner content interaction with the opportunities it provides. Holmberg (1983) places interaction at the center of interaction and communication theory, stating that the sense of belonging in learning environments makes learning enjoyable, that enjoyable learning motivates learners, that learner participation in decision-making processes increases motivation, and that this in turn supports learning. At the same time, extended reality enables learners and educators to present many objects, applications, and experiments that they cannot access or concretize in the real world due to various impossibilities in educational activities in many different dimensions at more affordable costs and without abstracting them from their real environment.

It is important to develop appropriate content and environments for the use of "Augmented Reality" applications, which can be applied in many different areas in a professional sense, in education and training. This requires not only technical teams that can respond to the needs of this technology, but also instructional designers and experts from different disciplines. In addition to technical teams capable of meeting the needs of this technology, it also requires instructional designers and experts from different disciplines.

The Metaverse and education

Technological developments in the last two decades have led to the rapid evolution of information and communication technologies. While computers have become more advanced in terms of hardware, innovations such as the Internet of Things, artificial intelligence and robotics have also led to significant advances in software. In particular, developments in mobile technologies such as Wi-Fi and Bluetooth, the widespread use of smartphones and tablets, the integration of 4G technology in the internet infrastructure and the steps taken towards 5G have greatly increased the use of the internet in daily life. This has made the use of digital technologies almost mandatory in solving problems encountered in areas such as health, education, banking, shopping, industry and tourism. One of the most prominent examples of this is the transfer of face-to-face activities to digital platforms during the novel coronavirus disease crisis affecting the whole world. During the global pandemic, countries have turned to various distance education applications and technological infrastructure in order to minimize learning losses and overcome deficiencies in education. In this process, many countries have aimed to ensure the continuity of learning by making a rapid transition from face-to-face to online education. This rapid transformation has increased the interest in learning methods using digital technologies in education and training and attracted the attention of field experts and educators (Talan, 2021).

Metaverse technology is one of the most notable examples of today's educational technologies. The Metaverse's areas of application include "laboratory simulations, studies aimed at developing operational skills, STEM education, and augmented and virtual reality-supported teaching." Unlike 2D education, the metaverse eliminates the limitations on participants' ability to express their emotions and interact in online education. In this context, thanks to the metaverse, students are able to access a richer, more interactive, and more practical learning experience (Aydın et al., 2023; Mystakidis, 2022; Yıldız and Bozkurt, 2023).

Metaverse technology is used in the learning and teaching of various fields (military, health, etc.). However, the use of metaverse technology in education differs significantly from its use in other fields due to its unique characteristics.

The transfer of education and educational content to metaverse environments appears to be possible with the development of technologies and the expansion of metaverse worlds. According to Jagatheesaperumal and colleagues (2022), traditional education and online education environments can be transferred to virtual spaces thanks to the Metaverse and Metaverse technologies. This will help these students have an engaging learning experience. According to Jeon and Jung (2021), new technological developments should leverage the potential of Metaverse-based platforms to enrich educational activities and learning experiences through information technologies such as artificial intelligence and big data. However, educational institutions must first focus on Metaverse-based education.

Kye and his colleagues (2021) have outlined some tasks for the use of the metaverse in educational applications. The first of these is understanding how students understand and interpret the Metaverse. It is important to carefully analyze why students like Metaverse environments, what they want to do in these environments, and what value they attribute to their avatars in virtual reality. In these environments, it is necessary to carefully examine students' activity levels, immersion levels (how much time they spend in the Metaverse environment), and the positive and negative effects this has on students' learning activities. Secondly, Metaverse environments allow students to experience events that they would not have the opportunity to experience in real life. However, students tend to accept the intentions of content developers and designers without criticism. Therefore, instructional designers and teachers who want to use the Metaverse for education need to collaborate and carry out projects in an original way in order to solve problems. To do so, they must correctly understand the technical characteristics and design classes of each type of Metaverse. Thirdly, it is necessary to develop an educational Metaverse platform to ensure that student data is not misused. There is also a need for evaluation studies on data collection to support teaching and learning.

The metaverse presents numerous possible uses within the field of education. For example, it can be used in areas such as medical, nursing and health education, science education, physical education, military training, production training and language learning. The Metaverse offers students the chance to engage, investigate, acquire knowledge, and instruct within a novel environment, while also facilitating interaction and collaboration with others. This virtual space allows learners to explore subjects that may be inaccessible in the physical world. For instance, individuals might not have the opportunity to assume a managerial role or practice piloting an aircraft. Nevertheless, if the developers intend to furnish users with experiential learning opportunities, they can effectively achieve this through the Metaverse. Consequently, the Metaverse presents numerous potential applications within the educational sector (Hwang & Chien 2022). Below are several justifications for the integration of the Metaverse into educational practices, without any significant omissions:

- Regularly immersing students in cognitive or skill-based practice settings that could pose risks or hazards in real-life situations.
- Consistently involving students in experiential learning contexts that are typically unavailable to them in real-world scenarios.
- To facilitate students' understanding of a scenario that necessitates sustained involvement and practice.
- Motivating students to develop or investigate concepts that may be impractical to implement in reality due to factors like financial constraints or the unavailability of physical resources.
- To facilitate students' involvement in innovative thinking and initiatives pertaining to their professional or personal lives.

- To facilitate students' ability to perceive, experience, or observe events from various perspectives or roles.
- To facilitate students' ability to engage and collaborate with individuals they might not encounter in real-world scenarios.
- Assisting students in discovering their potential and enhancing their higher-order thinking abilities through involvement in intricate, varied, and genuine tasks (Hwang & Chien 2022).

When local educational projects related to the metaverse are examined today, it is observed that Middle East Technical University (METU) researchers have developed a "virtual school" project in which students are represented through avatars and interact with other avatars in a 3D metaverse environment. In this project, virtual reality glasses are used to create educational environments that are closest to physical reality. From Türkiye perspective, it is understood that METU has implemented the first education model in the metaverse, and some private educational institutions have also started to make infrastructure investments for education in the metaverse (Altunal, 2022). The virtual world developed by DT Science (2021) at the international level offers students the opportunity to explore our solar system through augmented reality and provides an effective process of learning about the sun and planets through this environment. Master et al. (2020) emphasized in their study that the importance of distance education has increased during the coronavirus pandemic and that more realistic methods should be explored to increase the effectiveness and access of education. Jeon and Jung (2021) examined the potential of metaverse-based platforms in education. Research has revealed the effectiveness of the Metaverse environment in terms of foreign language learning (Liu & Zhang, 2012; Guo & Gao, 2022; Lee & Hwang, 2022). There are studies that applied training can be presented more effectively with virtual reality, for example, machine production parts are designed and training is carried out with various scenarios, and aircraft maintenance can be taught efficiently in the metaverse environment (Siyaev & Jo, 2021). Similarly, in chemistry education, many different chemistry courses are offered to students in a virtual laboratory environment (EON-XR, 2020). There are also suggestions that the metaverse should be used as a complementary model in education and that a hybrid education model should be adopted (Diaz et al., 2020). The Metaverse, defined as the Internet of the future, should be integrated with today's technologies and various applications (including e-learning systems) (Dahan et al., 2022). All the internet applications we are familiar with today will have the opportunity to have their own representation in the Metaverse (Guo & Gao, 2022).

As a result, it is observed that Metaverse technology is used in the field of education in applied sciences such as foreign language education, chemistry, medicine, engineering and technical sciences. In this framework, metaverse-based education has many potential application areas. The goals of learning in the Metaverse can become highly relevant to learners' real-life needs when there is no possibility to experience or apply them in the real world. In other words, metaverse-based education can be completely irrelevant to students' real-world professions or major fields. This may be due to students' willingness to take on different roles in order to gain new experiences or explore a different professional direction in the Metaverse (Hwang and Chien 2022).

The differences between Metaverse and online education

In the online education model, instructors and students continue their education process through various platforms such as Zoom, Teamviewer, Google Meet. Due to the nature of this model, students have limited interaction with their instructors and experience a lack of socialization (Anwar & Adnan, 2020).

In the realm of online education, it is frequently noted that students disable their cameras and disengage from the virtual classroom, despite the course being available. This behavior contributes to a reduction in interaction within the online educational framework. Furthermore, synchronous training conducted through two-dimensional web applications like Zoom and Google Meet can lead to considerable mental exhaustion. In asynchronous online learning, students may experience emotional isolation, which adversely impacts their motivation. Consequently, e-learning courses delivered on either synchronous or asynchronous platforms encounter elevated dropout rates (Mystakidis, 2022). However, in the metaverse environment, that is, in the three-dimensional virtual world, the presence of the student and his/her friends with their avatars increases the level of interaction. It is thought that this will strengthen the student's participation in the lessons and their sense of readiness. As a result, in the online education model, students are physically outside the educational environment, but in the Metaverse, they are in the educational environment.

The use of the metaverse world in education offers access to an unlimited virtual universe by eliminating physical limitations. The use of three-dimensional virtual glasses will enable participants to focus 100 %, as external distractions will be ignored. This is expected to significantly improve the quality of education.

Learning in the context of the metaverse does not overlap with synchronous or asynchronous online learning. Table 1 shows the differences between online learning and learning in the Metaverse (Jusuf et al., 2023).

Table 1. *Differences between Online Learning and Learning in the Metaverse*

Subject	Online Learning	Metaverse
Time and place of attendance of students	It takes place only when the teacher opens the meeting via video conference.	There are no time and place restrictions.
Student ID	Real Identity	Customized, dynamic digital identity (Avatar)
Learning Resource	Multimedia or online resources, usually asynchronous	Synchronous, visual or decentralized learning resources
Learning Activity	Lessons are often focused on lectures, participation in complex learning activities is difficult.	It allows students to participate virtually in various learning activities.
Learning Experience	It is usually based on online communication with video and audio.	It involves a lot of emotional interaction and expression.
Learning Objective	Low-level cognitive development is usually targeted.	Higher level cognitive development is easily achieved.
Learning Assessment	The focus is on learning outcomes.	It is combined with formative assessment.

Table 1 shows that online learning and metaverse-based learning exhibit significant differences in terms of time-space independence, identity usage, learning resources, and pedagogical approaches. While online learning is usually limited to the teacher initiating a video conference session at a specific time and place, learning in metaverse environments can be carried out in a sustainable manner without any time or place constraints. While students participate in online learning using their real identities, customizable and dynamic digital identities (avatars) are used in the metaverse. In terms of learning resources, online learning is mostly supported by asynchronous materials consisting of multimedia or online resources, while the metaverse provides a richer learning experience by offering synchronous, visual, and decentralized learning resources.

Online learning courses typically focus on lecture delivery, with limited participation in complex learning activities, whereas metaverse environments enable students to participate virtually in a variety of learning activities. While online learning is limited to video and audio-based communication in the context of learning experiences, metaverse learning processes are richer in terms of emotional interaction and expression. Furthermore, while online learning mostly targets lower-level cognitive development, metaverse applications support higher-level cognitive development and integrate with formative assessment processes.

The advantages and disadvantages of education in the Metaverse

It is a fact that the new generation of young people, called Generation Z or millennial children, are now much more interested and spend more time in virtual environments such as social media instead of watching TV. Although it is wrong to generalize by making a generational distinction, Generation Z, which refers to those born in 1995 and later in this generally accepted distinction, has been living in the internet and computers since its birth (Park & Kim, 2022). Considering that almost all university students are Generation Z and that this generation learns by observation, it is thought that educational materials to be created in three-dimensional virtual environments will attract the attention of new generation students much more. There are many scientific studies addressing the risks and advantages caused by the integration of metaverse into educational processes (Altunal, 2022; Lin et al, 2022; Onecha et al., 2023; Sükan & Dündar, 2023). Kaddoura and Al Husseiny (2023) listed the advantages and disadvantages of metaverse technologies in education as follows:

Advantages:

- Gamification: The increase in learner motivation, attitude and engagement through game-based learning. In Şentürk et al. (2022) study, it was concluded that the teaching methods realized with metaverse applications have benefits such as providing multiple visuals, being interesting, increasing students' participation, but also limitations such as high cost and restricting real communication between people compared to traditional teaching methods. Ağgül and Yalçın (2024), in their study on education and metaverse, stated that metaverse applications had a positive effect on students' self-confidence.

- Diversity and inclusion: Creating opportunities to overcome many real-world constraints such as socio-cultural, economic, physical differences and to benefit from opportunities. It can provide students with the opportunity to interact and communicate with students from different geographies or cultures (Artsın & Bağcı Sezer, 2022).

- Skill-Based Learning: Developing critical thinking, problem solving, collaboration, communication and technology skills, and providing the opportunity for as many repetitions as desired. Students can experience dangerous or impossible experiments that they would like to experience in real life (Muştu Yaldız & Kurubacak, 2022).

- Virtual Campus: Providing real-world experiences with challenging conditions through virtual campuses and offering accessible solutions for individuals with special needs. Students can virtually visit real-world environments such as historical sites, museums and laboratories (Çilesiz & Aydın, 2022).

- Enjoyable Learning Environment: Providing a pleasant learning environment by appealing to visual, auditory and tactile senses. Studies show that virtual reality technology in digital learning makes learning more fun and exciting for students (Lee & Hwang, 2022). It can provide students with a virtual learning environment (Ortega-Rodriguez, 2022).

- Visualized learning: Metaverse scenes have powerful and realistic visual effects, making learning effective. In the field of education, students can interact with their teachers and friends through their avatars, but they can also participate in their lessons in the virtual classroom and the elements that take place in the real classroom can also take place in the virtual classroom (Tlili, Huang, & Shehata, 2022).

Disadvantages:

- Expensive Background: It is a more expensive learning technology than traditional methods in terms of the need for fast internet, the cost of content creation and hardware costs. A good internet connection is required to ensure that the virtual world does not slow down or disconnect. Likewise, the user equipment that wants to benefit from the virtual world should have good hardware both in terms of processing capacity and graphics card (Diaz et al., 2020).
- Lack of Legal Restrictions: The lack of legal restrictions for metaverse environments raises security issues. Data collection and sharing with third parties can pose a major risk to the security of personal data (Christopoulos et al., 2021).
- Cultural Biases: The creation of social, cultural and economic inequalities for segments of society that do not master ICT.
- Usability and Accessibility Problems: It is not easy for some people to access and use metaverse technologies effectively. Creating a Metaverse environment requires high internet infrastructure, more technological computers, wearable technologies and energy. Therefore, the Metaverse environment, which is expected to provide equal opportunities, is expected to disrupt equal opportunities (Mystakidis, 2022).
- Time Constraints: Virtual and mixed reality devices cannot be used for long periods of time (one class hour) if they may cause discomfort or nausea. Nausea and dizziness are among the most commonly reported health issues related to VR (Pellas et al., 2021).
- Lack of Experts: The problems of not mastering and adapting to metaverse technologies have a negative impact on the perspective towards and willingness to use these technologies.

The lack of facial expressions in virtual classrooms in the Metaverse environment constitutes one of the biggest obstacles in terms of teaching. This lack of expression by both teachers and students can pose a significant problem in the virtual learning process. This is because facial expressions are one of the most critical elements of discussions in the virtual world as in real life. Although blinking has been added to avatars to solve this problem, requiring students to blink has not yet been effective in providing full reality, as well as the difficulties in training (Barry et al., 2015).

Conclusion

Technology, as a discipline that includes various elements such as methods, operations, processes and management and enables these elements to function in a certain order, builds a bridge between science and daily life (Alkan, 1984). Technology supports and helps the individual in every environment. In this context, education is also an important field where the effects of technology are seen. Integration of technology in education has become an inevitable situation (Taşkıran, 2017).

It is essential that education should be in accordance with the needs of the present age and be able to respond to the needs that may arise in the future (Aydın, 2003). Because education shapes the future generations of a society. Therefore, it is essential to equip individuals with skills such as accessing, organizing, analyzing and presenting information and communicating effectively. In this context, it is important to use technologies that will support the achievement of teaching objectives in education and training processes (Arslan, 2015). Moreover, the rapid development of technology increases the variety of digital materials in the learning environment. Thus, the integration and effective use of technology into the learning process transforms traditional learning-teaching methods (Kutlu, Uğuz, Günay, Etiz & Cihan, 2019). Metaverse technologies are also a part of this transformation.

The Metaverse is defined as a multidimensional and user-centered digital universe where physical and digital reality are integrated. Conceptually, the metaverse offers a continuous virtual environment where individuals interact, socialize, create content and experience through avatars (Lee et al., 2021). In this context, the metaverse is not only a technological development but also a new paradigm with transformative potential for education systems.

Virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) technologies are the fundamental technologies on which the metaverse is based. Thanks to these technologies, students experience a learning experience that involves multiple senses through active participation, in addition to visual and auditory learning during the teaching process. Indeed, according to Jung et al. (2021), these technologies contribute to increasing student motivation, learning retention, and strengthening conceptual learning. Among these technologies, augmented reality technology encompasses other levels of reality, enabling the creation of a comprehensive and enriched digital learning environment for students (Craig & Georgieva, 2023).

Compared to traditional teaching, in metaverse-based teaching, students participate in an individual or collaborative student-centered learning process in a virtual environment through avatars they create themselves. Indeed, Schroeder (2008) stated that education conducted in a virtual environment increases social communication among students and develops high-level scientific process skills and problem-solving skills. Therefore, it can be said that metaverse-based teaching supports scenario-based and interdisciplinary educational applications that enable students to develop various skills.cdx

There are many advantages to using the Metaverse in education. Thanks to interactive learning environments, students are transformed from passive recipients of knowledge to active producers of knowledge. In particular, applications such as simulations, virtual laboratories and three-dimensional modeling increase both the retention and accessibility of learning (Lee et al., 2021). Moreover, the elimination of geographical barriers and the personalization of learning content make the metaverse an inclusive learning platform. However, there are some limitations in the integration of this technology into education systems. Jung et al. (2021) emphasize that while the metaverse may create inequality due to its high hardware and infrastructure requirements, data security and ethical issues should not be ignored. It is stated that the digital pedagogical competencies of educators directly affect the success of this system; at the same time, negative psychological effects such as digital addiction and distraction should also be taken into consideration (Craig & Georgieva, 2023).

The integration of metaverse technology into teacher training processes offers significant opportunities in both theoretical and practical teaching dimensions in education faculties. Three-dimensional virtual campuses provide teacher candidates with the opportunity to receive training in interactive learning environments that transcend physical space limitations (Huang et al., 2021), while virtual classroom simulations contribute to the development of professional competencies such as classroom management, crisis resolution, and effective communication with different student profiles (Liang et al., 2022; Dalgarno & Lee, 2010). Especially in internships and observation programs, metaverse environments enable teacher candidates to prepare lesson plans for students of different levels and needs, implement these plans in virtual classrooms, and monitor their professional development through AI-supported feedback (Bailenson, 2018; Radianti et al., 2020). In addition, the metaverse enables teacher candidates to gain cross-cultural educational experiences and compare different educational systems by establishing international collaborations (Wang et al., 2023). However, in order for metaverse-based teacher training processes to be implemented effectively, it is necessary to develop digital literacy (Türel & Altun, 2023), provide hardware and infrastructure capabilities (Nedelcu & Dinu, 2022), and take the necessary measures regarding ethics and data security (Floridi et al., 2018).

The use of the metaverse in education should be considered not only as a technological innovation but also as a tool that supports environmental sustainability. Ecological contributions such as the potential to reduce the carbon footprint caused by face-to-face education should be integrated into strategic planning (Feng et al., 2022; Wang & Kim, 2023).

A strategic approach is needed for the effective and sustainable use of metaverse technology in education. Within this approach, priority is given to strengthening schools' internet infrastructure and providing equal access to every student in terms of hardware and software (Zhang et al., 2022). During this process, it is extremely important to provide teachers and students with training on digital literacy and ethical violations in terms of the sustainability of the metaverse approach (Li & Liu, 2023). At the same time, designing metaverse environments in a way that will enable students to acquire desired behaviors and ensuring that learning processes include student-centered and holistic activities will contribute to the sustainability of the metaverse (Bailenson, 2018; Akçayır & Dündar, 2023). In addition, ethical violations and the establishment of national-level education policies and standards regarding data security will strengthen the long-term integration of the metaverse into educational environments (Floridi & Taddeo, 2016; OECD, 2021).

In conclusion, the metaverse is not just a technological innovation; it is a learning ecosystem with the potential to radically transform educational processes. However, for this transformation to take place in a healthy way, not only technical equipment is not enough, but also multifaceted factors such as pedagogical approaches, ethical principles, social equity and cultural sensitivity need to be taken into account. The sustainable, accessible and pedagogically meaningful use of metaverse technologies in education will be possible through multidisciplinary collaborations and long-term strategic planning.

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AUGMENTED REALITY APPLICATIONS IN SCIENCE EDUCATION: FOOD CHAIN EXAMPLE

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Introduction

The 21st century education paradigm requires students to grow up as individuals who not only access information, but also analyse, synthesise and use it effectively (OECD, 2018). In this direction, the integration of innovative instructional technologies into learning processes as well as traditional educational approaches is becoming increasingly important (Schunk, Pintrich & Meece, 2014). Augmented reality (AR) applications, one of the reflections of technological developments in education, provide students with the opportunity to concretise abstract concepts, create interactive learning environments and offer more permanent learning experiences (Dunleavy & Dede, 2014; Wu et al., 2013).

Science education has a structure based on observation, experiment and application by nature. However, it is difficult to directly observe and experimentally apply some topics in the traditional classroom environment (Gilbert, 2006). Although the food chain is a critical concept in terms of understanding ecosystem dynamics, students may find it abstract and may contain conceptual errors (Çil, 2016; Tansel, 2019). At this point, augmented reality technologies are thought to be a powerful tool that can help students better understand the concept of food chain (Billinghurst, Clark & Lee, 2015).

Augmented reality enables learners to experience virtual and physical components simultaneously by integrating digital objects into the real world environment (Azuma, 1997). In this way, students can observe the energy flow in the ecosystem, explore the interactions in different links of the food chain with three-dimensional visuals, and learn ecological balance by experiencing (Cheng & Tsai, 2013). Studies show that augmented reality-supported science education positively affects students' academic achievement and conceptual understanding (Ibáñez & Delgado-Kloos, 2018; Sotiriou & Bogner, 2008).

It is emphasised that interaction and active participation of students are critical in the learning process (Bruner, 1966; Vygotsky, 1978). In this context, interactive learning environments offered by augmented reality technologies allow students to be involved in experimental processes and learn concepts by exploring them (Dunleavy, Dede & Mitchell, 2009). In traditional science teaching, concepts such as ecosystem and food chain are usually explained through schematic drawings or two-dimensional materials. However, these methods may not be effective enough for students to construct their mental models (Trevors & Duffy, 2004). At this point, augmented reality applications encourage permanent learning by providing students with a dynamic, interactive and in-depth learning experience (Küçük, Yılmaz & Göktaş, 2014).

Studies on the integration of augmented reality technologies into science education reveal that such applications increase students' motivation, accelerate learning processes and support permanent learning (Bacca et al., 2014; Radu, 2014). In addition, it is stated that AR applications create student-centred learning environments and thus enable students to direct their own learning (Kerawalla et al., 2006). The use of augmented reality technologies, especially in teaching abstract subjects, increases students' conceptual understanding levels and reduces their cognitive load (Wu et al., 2013).

Considering the importance of affective and cognitive factors in terms of learning processes, it is stated that augmented reality applications increase student interest and motivation and make learning fun (Sundar, Kang & Oprean, 2017). Research in the context of science education shows that technology integration in learning environments improves students' science process skills and increases their metacognitive awareness (Hwang, Wu & Ke, 2011; Linn, Davis & Bell, 2004). In this context, it can be said that augmented reality technologies play an important role in education by contributing to experimental and discovery-based learning processes in science.

According to the Turkish Century Education Model, the subject of food chain is addressed at the 8th grade level within the scope of science course. However, in this study, 3rd grade primary school students were selected as the research group. The main reason for this preference is to reveal how effective augmented reality applications are not only at higher grade levels, but also at younger age groups who meet abstract concepts for the first time. It is foreseeable that augmented reality will support meaningful learning in 8th grade students.

In this context, based on the "Journey to the World of Living Things" unit at the 3rd grade level, the study was based on the students' ability to recognise, classify and distinguish the feeding styles of animals; in line with these acquisitions, it was examined how students' pre-learning of the concept of food chain could be supported through augmented reality. In this way, it is aimed that students will be better prepared for higher level concepts such as ecosystem and food chain that they will encounter in the following years.

Thanks to Animal 4D+, one of the AR applications, students can observe different animal species in three dimensions and with sound, and can directly experience what these animals feed on. For example, by observing a frog eating insects, a rabbit feeding on carrots or a monkey consuming bananas, students can learn the distinctive differences between carnivorous, herbivorous and omnivorous creatures and comprehend the nutritional relationships between living things through concrete examples. Thus, the food chain, which is a complex subject for students in this age group, whose abstract thinking skills are not yet fully developed, has been concretised and presented in a way appropriate to their age level. It is predicted that these experiences gained at an early age will make students' future science learning processes more in-depth, meaningful and permanent.

The problem statement addressed in this study: "To what extent does augmented reality supported teaching contribute to the 3rd grade students' skills of recognising, classifying and distinguishing the diet of animals and their pre-learning of the concept of food chain?". The sub-problems created to explain this problem situation are as follows.

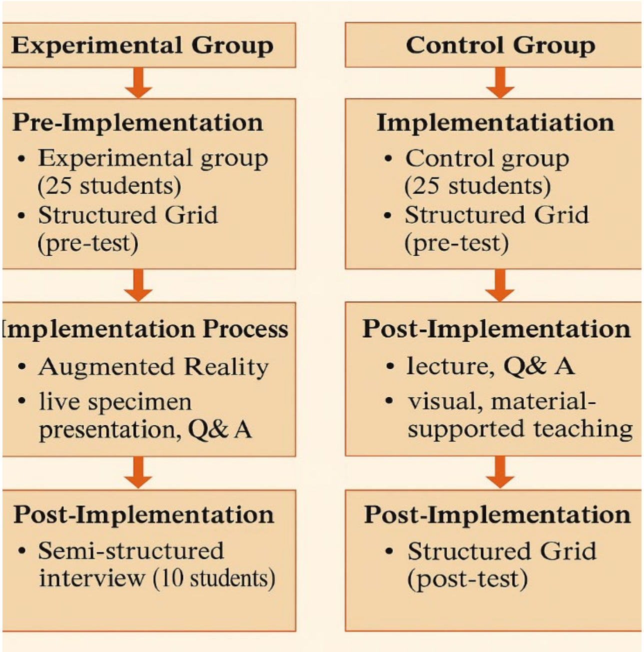
- Do the students in the experimental and control groups differ significantly in their pre-test scores?
- Is there a statistically meaningful change in the control group students' scores from pre-test to post-test?
- Is there a statistically meaningful change in the experimental group students' scores from pre-test to post-test?
- Do the post-test scores of the experimental and control group students show a significant difference?
- What insights did students in the experimental group share regarding their experience with augmented reality-based science education?

Method

Research model

This study was carried out using the explanatory sequential mixed method design, where both quantitative and qualitative approaches are employed in a consecutive manner. Initially, the research began with a quantitative phase, followed by a qualitative phase to gain deeper insight into the findings (Creswell & Clark, 2018). The quantitative data were gathered through a quasi-experimental pretest-posttest design involving both experimental and control groups. In the next phase, qualitative data were obtained via semi-structured interviews to explore students' perspectives more thoroughly. This approach allowed for a comprehensive evaluation of how augmented reality-enhanced science instruction influenced students' conceptual understanding. Furthermore, the experimental group's reflections on the instructional experience were analyzed in detail. The process model is illustrated in Figure 1.

Figure 1. *Process Oriented Model*



Working group

The research sample consisted of 50 third-grade students enrolled in a public primary school located in Ankara during the 2024–2025 academic year. Among these students, 25 were assigned to the experimental group, while the remaining 25 formed the control group. The assignment was made using a paired sampling method, ensuring the groups had comparable academic achievement levels (Büyüköztürk et al., 2020

Data collection tools

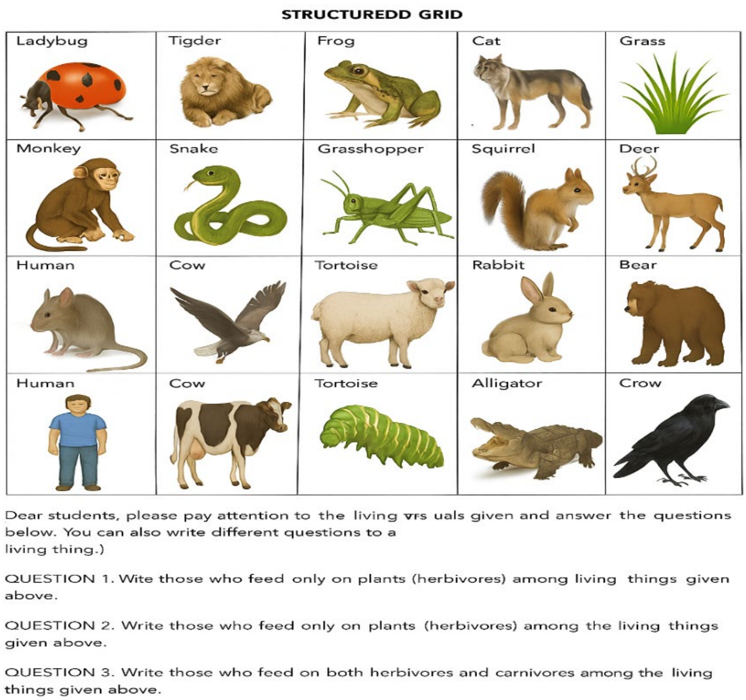
Structured grid

In the study, a structured grid prepared by the researcher in line with the opinions of field experts was used to evaluate the 3rd grade students. This measurement tool was designed to determine the students' level of recognising, classifying and distinguishing the diet of animals.

Structured grid is a measurement technique in which the possible answers on a subject are written in boxes and students mark the appropriate answers to the questions by selecting them from these boxes (Kaçan, 2008). This technique is especially used effectively to determine misconceptions and knowledge deficiencies in students (Bahar et al., 2002). In addition, it allows students to be more mentally active by providing them with the opportunity to make predictions (Durmuş & Karakırık, 2005). In structured grid application, it is generally not possible for students to give correct answers without having prior knowledge about the subject. This situation allows students' incomplete or incorrect learning to be easily identified through the selected boxes (MEB, 2004).

In addition, the structured grid technique allows students to measure not only their level of knowledge but also their ability to associate information and use it in logical integrity (White & Gunstone, 1992). In this respect, it is an effective tool in revealing students' conceptual understanding, especially in disciplines such as science where the relationships between concepts are intense (Çepni et al., 1997). In this context, the structured grid revealed in a multidimensional way how students perceived the concepts (animal characteristics, classification, and diet) in the study. The grid was applied to the experimental and control groups as both pre-test and post-test. The prepared structured grid is given in Figure 2.

Figure 2. *Structured Grid*



In the scoring of the structured grid, there are two different scoring methods in the literature. For example, the first question is a ranking question. In such questions, the correctness of the order given by the students is taken as a basis; 1 point is given for each correct matching and 0 points are given for incorrect ones. As soon as the student receives 0 points, the other answers are not taken into consideration. Sample answers and their scoring are given below.

Sample answers:

Grass → *Grasshopper* → *Frog* → *Snake* → *Eagle* = 5 points

Grass → *Grasshopper* → Rabbit → Snake → Eagle = 2 points

Grass → Snake → Frog → Grasshopper → Eagle = 1 point

In the scoring of the other questions, each correct answer was scored as 1 point and the wrong answer was scored as 0 point. For example, the student who gave seven different answers in the second question (cow, sheep, rabbit, deer, squirrel, caterpillar and grasshopper) received full points (7 points); the student who gave seven different answers in the third question (tiger, eagle, snake, fox, frog, crow, crocodile) received full points (7 points); the student who gave five different answers in the fourth question (bear, monkey, mouse, human, crow) received full points (5 points).

Semi-structured interview form

To explore the views of the students in the experimental group regarding the augmented reality-based instructional process, a semi-structured interview form including four open-ended questions was created. The form was drafted based on expert feedback in the field and underwent a pilot study prior to its actual use.

Implementation process

As part of the unit titled *"Journey to the World of Living Things"*, instructional content related to animals, their nutrition, and the food chain was delivered to both the experimental and control groups. The sessions were conducted by the same teacher and spanned a total of eight class hours.

Experimental group application

Within the scope of the "Journey to the World of Living Things" unit, content about animals and their diet was presented to the students through the Animal 4D+ augmented reality application. During the application, students observed animals in three dimensions, listened to their voices and visually experienced what they feed on. This process was supported by teacher-guided presentation, question-answer and discussion methods. Visuals for the process are given in Figures 3 and 4.

Figure 3. *Visuals for the Process 1*

Figure 4. *Visuals for the Process 2*

Following the AR-based learning activities, the teacher introduced the concept of the food chain to the students. Using visuals displayed on the smart board, the connections among living organisms within a food network were explained. Subsequently, the students were grouped, and each group received materials such as cardboard, colored paper, crayons, scissors, and tape to create a poster illustrating a food chain. The activity concluded with each group presenting their work on the board, marking the end of the session.

Control group application

Students in the control group engaged with the same content using more traditional instructional strategies, including teacher presentations, visual aids, class discussions, and Q&A sessions. The teacher emphasized student engagement while presenting various animal visuals on the smart board and explaining their dietary habits. Later, visuals of food chains were shared to enhance understanding. Similar to the experimental group, students collaborated in small groups, received the necessary materials, and were tasked with designing a food chain poster. Each group showcased their posters to the class, completing the learning activity.

Examples of posters made by both experimental and control groups are given in Figure 5.

Figure 5. *Food Chain Sample Posters of Experimental and Control Group Students*

After the teaching process was completed in both groups, the post-test was applied.

Findings

Quantitative data analysis results

Firstly, it was analysed whether the data showed normal distribution or not. The results of the analyses are given in Table 1.

Table 1. *Normality Test Results for Data*

Test	Group	Shapiro-Wilk		
		Statistics	sd	*p*
Pre-test	Experiment	0.92	25	.058
	Control	0.91	25	.033
Post-test	Experiment	0.92	25	.055
	Control	0.94	25	.154

According to the findings presented in the table, all data sets demonstrated a normal distribution at the .05 significance level, with the exception of the control group's pre-test scores. Nevertheless, the skewness and kurtosis values for this data fell within the acceptable range of -1.5 to +1.5. Additionally, the mode, median, and mean values were observed to be closely aligned. Taking these indicators into account, it was concluded that the control group's pre-test data could also be considered as normally distributed.

Table 2 shows the unrelated sample t-test conducted to examine the problem situation " Do the students in the experimental and control groups differ significantly in their pre-test scores?".

Table 2. *Results of the Analysis of Experimental and Control Group Pre-Test Scores*

Test	Group	n	$\bar{x}$	s	sd	t	*p*
Pre-test	Experiment	25	7.68	2.66	24	.108	.914
	Control	25	7.60	2.58	24		

According to the table, there is no significant difference between the pre-test results of the experimental and control group students, $p=.914>.05$. This is an indication that the readiness levels of both groups are the same.

Table 3 shows the paired sample t-test conducted to examine the problem situation " Is there a statistically meaningful change in the control group students' scores from pre-test to post-test?".

Table 3. *Analysis Results of Pre and Post Test Scores for the Control Group*

Control	n	$\bar{x}$	s	sd	t	*p*
Pre-test	25	7.60	2.58	24	-10.07	.001
Post-test	25	12.76	2.57			

Based on the results in the table, the analysis revealed a statistically significant difference between the pre-test and post-test scores of students in the control group, $t(24) = -10.07$, $p = .001 < .05$. The post-test scores ($\bar{x}_{\text{post}}$ = 12.76) were notably higher than the pre-test scores ($\bar{x}_{\text{pre}}$ = 7.60), indicating a performance improvement following the intervention.

Table 4 shows the paired sample t-test conducted to examine the problem situation " Is there a statistically meaningful change in the experimental group students' scores from pre-test to post-test?".

Table 4*. Analysis Results of Pre and Post Test Scores for the Experimental Group*

Experiment	**n**	**x̄**	**s**	**sd**	**t**	***p***
Pre-test	25	7.68	2.66	24	-12.84	.001
Post-test	25	18.00	3.20			

The statistical analysis in the table shows that a meaningful difference exists between the pre-test and post-test scores of students in the experimental group, $t(24) = -12.84$, $p = .001 < .05$. The increase in performance is evident, as the average score in the post-test ($\bar{x}_{\text{post}}$ = 18.00) was considerably higher than the pre-test average ($\bar{x}_{\text{pre}}$ = 7.68).

Table 5 shows the unrelated sample t-test conducted to examine the problem situation " Do the post-test scores of the experimental and control group students show a significant difference?".

Table 5. *Results of the Analyses Related to the Post Test Scores of the Experimental and Control Groups*

Test	Group	n	x̄	s	sd	t	*p*
Post-test	Experiment	25	18.00	3.20	24	11.70	.001
	Control	25	12.76	2.57	24		

As shown in the table, a statistically significant difference was found between the post-test scores of the experimental and control groups, $t(24) = 11.70$, $p = .001 < .05$. The mean score of the experimental group ($\bar{x}_{\text{experimentalpost}}$ = 18.00) exceeded that of the control group ($\bar{x}_{\text{controlpost}}$ = 12.76), indicating that the intervention had a more positive impact on the experimental group's performance. This outcome highlights the effectiveness of augmented reality-based instruction.

Qualitative data analysis results

The following questions were included in the semi-structured interview form conducted with 10 students who were voluntarily selected among the experimental group students.

- *Do you like this application? Why?*
- *What did you like most about the app?*
- *Have you learnt anything new about animals? What have you learnt?*
- *Did you find out how the animals you saw were fed? Can you give some examples?*

The thematic analysis of the answers given by the students is given in Table 6.

Table 6. *Thematic Analysis Results*

Articles	Theme	Code	Frequency
Do you like this application? Why?	General	Like	10
	Reasons for liking	It's fun	4
		Different	3
		Informative	3
What did you like most about the app?	Favourite aspects	Sounds	5
		Movements	3
		Eating food	2
Have you learnt anything new about animals? What have you learnt?	Learning outcomes	Their appearance	3
		Their voices	4
		What they eat	3
Did you find out how the animals you saw were fed? Can you give some examples?	Learning	Yes	10
	Examples	Frog eats flies	4
		Cow eating grass	2
		Elephant eating grass	3
		Monkey eating a banana	1

Some examples of the answers given by the students to the questions are as follows:

"It was a lot of fun."

"It was very informative."

"It felt different, I've never seen anything like it before."

"The monkey had a funny voice."

"The frog moved."

"It was nice to watch them eat."

"The elephant ate grass, so it's a herbivore."

Conclusion, Discussion and Suggestions

This study investigated how augmented reality (AR)-enhanced science instruction affected the ability of third-grade primary school students to recognize and classify living organisms, identify their dietary habits, and comprehend the concept of the food chain. Analysis of the quantitative data revealed a notable improvement in the pre-test to post-test scores across both the experimental and control groups. These results suggest that the instructional strategies employed, whether traditional such as direct instruction, discussions, and Q&A sessions, or AR-based, had a positive impact on students' learning outcomes.

Nevertheless, when comparing the post-test performances of the two groups, the experimental group outperformed the control group to a statistically significant degree. This outcome highlights the potential of augmented reality to enhance learning, particularly in topics that require a high level of conceptual understanding or involve abstract concepts.

Qualitative data also support this result. The students who participated in the semi-structured interviews stated that they liked the application very much and that they were especially interested in the movement of animals, making sounds and animating feeding moments. The students stated that thanks to the application, they gained new information about the appearance of animals, their voices, what they feed on and the feeding relationships formed by these creatures. All students stated that they were able to distinguish between herbivorous, carnivorous and omnivorous creatures, create a food chain using this information and learnt this concept during the application process.

The results obtained reveal that augmented reality technology enables students in young age groups to understand both abstract concepts such as the food chain and the basic properties of living things more easily. Such interactive digital content, which is presented in accordance with the age levels of the students, strengthened learning gains in both cognitive and affective terms. In this context, it can be said that teaching processes supported by augmented reality applications can be an effective tool in structuring students' prior learning towards more complex concepts that they will encounter in the future.

The findings of this study revealed that augmented reality technology is an effective teaching tool for young age groups, especially in teaching abstract concepts such as food chain. The fact that the students in the experimental group reached meaningful learning levels shows that augmented reality environments offer important opportunities in terms of cognitive development and conceptual structuring.

This finding is in parallel with the study conducted by Ibáñez and Delgado-Kloos (2018). The researchers stated that augmented reality-supported science education strengthens students' conceptual understanding and makes abstract knowledge concrete. Similarly, Sotiriou and Bogner (2008) found that augmented reality technologies have positive effects on students' scientific process skills and that these applications facilitate the internalisation of scientific concepts, especially at the primary school level.

The findings obtained through the semi-structured interviews indicated that students showed strong interest in the learning process and held positive views toward the augmented reality application. Similar results were noted in Radu's (2014) meta-analysis, which reported that AR implementations contributed to increased student engagement, extended their attention span, and enhanced motivation levels. These outcomes align with the experimental group's notable academic success and favorable feedback throughout the study.

Furthermore, Wu et al. (2013) highlighted that augmented reality tools support conceptual understanding by minimizing cognitive overload. This perspective is reinforced by the present study, where third-grade students effectively differentiated between carnivores, herbivores, and omnivores, linked these classifications to animal traits, and successfully constructed food chains. These findings underscore the value of AR-based environments in fostering deep and lasting learning experiences, particularly among younger learners.

The observed improvement in learning outcomes among control group students suggests that conventional instructional strategies—such as presentations, visual explanations, and interactive questioning—still maintain their educational effectiveness. Nevertheless, the experimental group's post-test scores were notably higher than those of the control group, indicating that the integration of augmented reality significantly enhanced learning outcomes and promoted longer-term retention. These results are consistent with the findings of Cheng and Tsai (2013), who emphasized that AR-supported environments foster deeper cognitive engagement and facilitate conceptual transformation in learners.

In light of these findings, the following recommendations are presented:

- Augmented reality applications should be given more space at primary school level. Especially in teaching abstract concepts, such digitally supported methods attract students' attention and support permanent learning.
- Augmented reality applications are effective in terms of achieving not only cognitive but also affective goals. For this reason, applications that appeal to multiple senses that will increase student motivation and participation should be prioritised in course designs.
- The current research was carried out with a relatively small sample of students. Future studies involving various age groups, socioeconomic backgrounds, or alternative science topics would help improve the generalizability of the results.
- To gain deeper insights into students' learning experiences, qualitative data collection processes can be enriched through extended observations and the analysis of student-generated artifacts.
- Enhancing teachers' digital pedagogical skills is essential for the effective and appropriate use of emerging technologies. Accordingly, it is recommended that augmented reality tools be integrated into professional development and in-service teacher training programs.

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USE OF TECHNOLOGY IN STEM CLASSROOMS

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Introduction

Today, countries are in a race in areas such as the economy, technology, and industry. In order to be successful in this race, they need individuals who develop themselves in the fields of science, technology, engineering, and mathematics (STEM) and have a profession. Accordingly, the skills, job conditions, and job descriptions expected from individuals who will take part in the business world of the future are also changing. In the Future of Jobs Report published by the World Economic Forum (WEF) (2025), it is stated that technological developments such as artificial intelligence, data analytics, and automation will cause radical changes in today's business world. It is emphasised that these changes will lead to the loss of some existing jobs and the emergence of new professions and skills (WEF, 2025). According to the report, in the near future, the skills that students should have and the professions they may be oriented towards are expressed in Table 1.

Table 1. *Occupations and Skills Required for the Labour Force by 2030*

Occupations	Skills
Technology and Digital Transformation Areas • Artificial Intelligence and Machine • Learning Expertise • Data analysis and Data Science • Cyber Security Expertise • Cloud Computing and Network Engineering *Green Technologies and Sustainability* • Renewable Energy Expertise • Sustainability Experts *Health and Life Sciences* • Biotechnology and Genetic Engineering • Digital Health and Tele-Medicine Expertise *Areas requiring Creativity and Human Skills* • Educational Technologies and Educational Consultancy • Design and Creative Arts • Psychology and Human Behaviour Analysis *Business and Management Areas* • Project Management • Financial Technology (FinTech) Expertise	Artificial Intelligence and Big Data Technological literacy Networks and Cyber Security Curiosity and Lifelong Learning Creative Thinking Endurance, flexibility, and agility Leadership and Social Impact Analytical Thinking Talent Management Environmental Responsibility

These 21st-century skills, which are expressed as 21st-century skills, are considered important for individuals who will take part in the business world of the future and are the professions expressed in the table to acquire during their education. Countries that are aware of this situation implicitly or explicitly include the teaching, use and application of technology in their curriculum to gain these skills. Therefore, STEM education is one of the approaches that these countries have included and started to implement in their curricula in recent years.

STEM education

STEM education is an application of pedagogical approaches based on technology/engineering designs to teach the content of science and mathematics courses and to do so in combination with technology/engineering applications (Sanders, 2012). Students need to justify the relationship of the lessons they learn with real life and career choices, and to be able to see these justifications clearly (Gomez & Albrecth, 2014). STEM education is a learning approach that eliminates the traditional barriers separating science, technology, engineering and mathematics from each other and integrates these disciplines with learning experiences compatible with the real-world (Vasquez, et al., 2013).

The term STEM generally emphasises science and mathematics, while technology and engineering are less emphasised (Bybee, 2010). This is because school curricula predominantly include science and mathematics (Vasquez et al., 2013).

Science is in STEM education covers natural sciences such as chemistry, physics and biology and key concepts, principles and generalisations in these fields (Jorgenson et al., 2014). In STEM, students solve real-life problems that they face and have to overcome by associating scientific laws and knowledge with technology and engineering (Jolly, 2017).

The technology meant in STEM is what the results of the designs developed to meet people's wants and needs are, and while making their designs, they can benefit not only from digital tools but also from everything they use in daily life (Jorgenson et al., 2014). Technology creates opportunities for students to realise and discover that science, technology, and mathematics education are intertwined through investigation, research, and problem solving (Mahiroğlu & Karaağaçlı, 2005).

Engineering is the strongest component that holds the other three fields together in STEM. While students design products and models to solve a problem, they use engineering practices to apply science and mathematics concepts in this process (Jolly, 2017).

In STEM education, mathematics is not only about numbers and operations. Students use their mathematical knowledge and skills to analyse, justify, and interpret solutions to various real-life problems (Jolly, 2017).

The sub-disciplines of STEM education, which can be applied in all teaching processes from pre-school to university, are given in Table 2 (Ayvacı, 2017, p. 249).

Table 2. *Sub-Disciplines of STEM*

Science	**Technology**	**Engineering**	**Maths**
Biology Chemistry Marine biology Physics Science Environmental science Geology	Computer/ Information Systems Game design Planning Web/ Software planning	Chemical Engineering Civil Engineering Computer Engineering Electrical / Electronic engineering Mechanical engineering Environmental engineering	Maths Geometry Statistics ......

In recent years, both in the world and in Türkiye, curricula supported by STEM outcomes have been designed by focusing on skill-oriented teaching. Updated in 2024 and prepared within the scope of the Turkish Century Education Model, the Science Curriculum adopts a teaching approach that encompasses 21st century skills; it is aimed to raise individuals who research, question, think critically, cooperate in learning processes, take an active role in group work, have self-regulation skills, exhibit scientific attitudes and behaviours, are environmentally sensitive, are aware of digital transformation, adapt to technology, and have the holistic skills required by the age; and to integrate the skills of the learning process based on science, technology, engineering and design through interdisciplinary relationships (Ministry of National Education [MoNE], 2024). These goals overlap with the goals of STEM education, which aims to gain and develop 21st-century skills.

Alongside the fast growth of technology, its various applications in educational settings are becoming increasingly common. Examples of these applications are simulation, augmented reality, problem-based learning, coding, robotic applications, and artificial intelligence (Çömek & Avcı, 2016). Even though educators recognize how crucial technology is for teaching and learning, they often do not include it in their classes (O'neal, et al., 2017). However, it is not possible for any teacher to use all available technologies (Bender, 2017). Although it is impossible to implement all technologies for almost everyone, a number of technologies that have proven to be useful in STEM lessons by Bender (2017) are given in Table 3.

Table 3. *Some Technologies that can be used in STEM Lessons*

Wi-Fi and Computer Connection in STEM Classrooms	• The first target of technology should be an internet connection in every school and every classroom. • Blogger (www.blogger.com): Blogging about topics covered in class increases student interest and understanding. While making them think about what STEM can mean in non-science courses, it also instills technology. • Dropbox (www.dropbox.com): Dropbox is a secure place for digital information; teachers can communicate with students by dropping almost any digital file into Dropbox. • Gliffy (www.gliffy.com): Technical drawings and diagrams are very critical in STEM. With Gliffy online diagramming software, high-quality diagrams, flowcharts, and technical drawings can be made easily. • Glogster (www.edu.glogster.com): This software allows students and teachers to make online posters, magazines, and digital video files. • Google Sites (www.google.com/sites): Google Sites provides STEM teachers with the opportunity to design free web pages. • Scribd (www.scribd.com) allows teachers to upload documents such as lecture notes, PowerPoint presentations, or PDF files to share with their students.

	• Survey Monkey (www.teachertrainingvideos.com/monkey/index.html) allows teachers to create surveys for the class on any topic they want. • Poll Everywhere(www.polleverywhere.com): Another tool that allows teachers to survey students or anyone about topics in the classroom. It can also be used to make a digital quiz.
Smart Board	• Interactive assignments can be created. • Students can present their projects.
Computer-Aided Education	• Successmaker maths or Successmaker science is one of a range of commercially available curricula for nursery to secondary school: http://www.pearsonschool.com • The Academy of Mathematics is a well-designed, well-researched, commercially available Year 2 to Year 12 curriculum that delivers significant academic progress: http://eps.schoolspecialty.com • SAS Curriculum Pathways (sascurriculumpathways.com) provides an extensive range of free online educational resources, including lesson plans and activities for subjects like English, language arts, science, social studies, math, and Spanish. While this is not a curriculum in and of itself, it is a high-quality supporting curriculum that will enhance any STEM classroom.
Khan Academy	• Khan Academy is a free online maths, chemistry, and physics curriculum hosted in the cloud and representing anytime, anywhere learning, with some content in other areas as well.

Teachers' utilization of one or more of these technologies throughout the academic year enables teachers to stay up-to-date with technology-based teaching and not to be overwhelmed by innovations in this field (Bender, 2017).

Coding and robotic applications in STEM classrooms

The skills that STEM education wants to provide are 21st-century skills such as critical thinking, problem solving, collaboration, and creativity. While preparing today's students who will take part in the business world of the future for life, one of the ways to provide these skills to students is by integrating them with technology, such as coding education. In today's world, coding is an essential skill for students and professionals across various sectors in the business environment.

Coding involves teaching students' computer programming using simple programming languages aimed at younger students. Coding is basically learning to tell a computer or other machines (such as robots) what to do (Bender, 2017). With the integration of STEM disciplines and coding within the scope of STEM education, it is aimed to concretize abstract subjects, to make learning meaningful, and to raise individuals with 21st-century skills instead of rote, unquestioning, and uncritical generations (Gültepe, 2018).

The aim of coding education is not to train everyone as a computer programmer; on the contrary, it is a way to create ways for students to gain 21st-century skills such as problem solving and collaborative working, which STEM education aims to provide (Bender, 2017). In coding education, students are expected to follow the instructions (codes) they write on computers step by step, analyze, synthesize, and evaluate the data obtained, then go back to the beginning and make corrections, thus minimizing the errors that may arise (Şenol & Demirer, 2017). Basic coding logic consists of the given, desired, and solution generation stages. Coding logic is becoming an important part of daily life, both in industry and in schools. In societies with rapid information growth, it brings about rapid development and change in people. Learning programming helps people develop skills such as problem solving, creative and systematic thinking, and seeing the relationships between events (Güleryüz et al., 2020).

Looking at the situation of coding education in the world, important studies have been carried out in coding and STEM education with the "Bridge Project" implemented by the University of Denver in the USA. Again, with the "Tynker Project", which was launched in 2012 in the USA, it aimed for students to learn to build games, applications, and coding (Karal et al., 2017). In addition, with "code.org" and "coding hour" activities, tens of hours of coding curricula were created and coding Olympiads were organized (Yüksel et al., 2025). However, in many other countries around the world, coding is taught at all grade levels, and these codes are used to program computers or code robots. For example, in the UK, all students start learning coding at the age of 5; in Estonia, they learn programming to make computer games in the first grade, and in Singapore, they start coding in primary school (Bender, 2017). The main reasons why countries in Europe include coding in their curricula are that they aim to improve students' logical thinking and problem-solving skills (Yüksel et al., 2025). In Türkiye, the Ministry of National Education has accepted the gradual introduction of the Information Technologies and Software course starting from the 5th grade in the 2012-2013 academic year. In this course, it is advised to utilize collaborative coding platforms that focus on sharing and developing together (MoNE, 2015). In 2018, robotics and coding courses were included in the Information Technologies and Software Curriculum with the topics of "Problem Analysis and Solving Approaches", "Algorithm and Strategy Development (algorithm creation logic, pseudocode, flowcharts, etc.)", "Programming", "Software Project Development, Implementation and Dissemination" (MoNE, 2018). In addition, in the 2023 Vision Plan (2018), it is planned to integrate information production skills such as coding, 3D design, electronic design into learning processes through studies to be carried out at primary, secondary and high school levels, at school and out of school, for students, teachers, educational administrators, public, curriculum and educational content (Karataş, 2021).

With coding education within the scope of STEM applications, it may be possible to raise individuals with the skills that enable students can compete in the global market of the future. In this context, the benefits and gains of coding education in STEM-based applications can be listed as follows (Güleryüz et al., 2020):

- It saves science from being an abstract concept. It transforms scientific endeavours into a tangible, exciting tool.
- By enabling them to use science to solve real-life problems, it teaches them to be curious, to find solutions, and gives them the confidence to ask questions.
- It enables them to get excited about science by experiencing and exploring engineering, technology, and software.

- Achievements
- Creating a program and writing the code for that program
- Using logical reasoning grounded in computational methods
- Being capable of performing tasks while keeping in mind the code and variables
- Discovering the quickest way to solve issues
- Being able to view situations and challenges from various angles
- Organized and innovative thinking
- Acquiring knowledge of an actual programming language

While there are many good reasons to teach coding as a stand-alone subject in schools, coding in the STEM context is often combined with robotics (Bender, 2017). Robotics refers to the process of realizing the effect of coding on objects (Karataş, 2021). The goal of robotics education projects is to give teachers a robotics program that combines science and technology, helping students learn in a way that is more engaging and lasting by incorporating robotics and cutting-edge technology into their education (Wood, 2003). Within the scope of STEM applications, robotics enables us to see, try, and measure the results of an important method in the real world thanks to coding. Thus, an important tool such as robotics is gained in education for teaching abstract concepts by concretizing them (Güleryüz et al., 2020).

Robotic coding is a type of coding that students create by combining mechanics and coding, and allows students to obtain a physical result from the code they write (Güleryüz, 2020). In other words, when the student sees that he moves robots with the codes he writes, coding becomes more fun for him, and he improves himself while playing games (Karataş, 2021). In addition, robots are objects that are especially interesting to children. Doing activities with robots provides a high motivation for children (Güleryüz et al., 2020).

Robots teach students the scientific method, coding logic, and engineering design processes in a fun way, while at the same time developing their problem-solving, collaborative working, and mathematical thinking skills, and creativity (Fidan & Yalçın, 2012). The use of robots in STEM education provides great opportunities for students to gain these skills. Some of the benefits of using robotic applications in STEM classrooms are as follows (Benitti & Spolaôr, 2017):

- It gives students the opportunity to handle the theoretical knowledge they have acquired in the fields of science, technology, engineering, and mathematics by combining it with real life problems.
- By working with robots, students have the opportunity to develop 21st-century skills such as innovation, critical thinking, and problem solving.
- Robotic applications create a rich and engaging learning environment for STEM education.
- Motivates and inspires students to learn STEM disciplines.
- Robotic applications can also be used to teach the concepts of STEM disciplines.

Today, the use of robot coding software, physical robots, and virtual robot coding environments in robotic coding teaching is quite high (Güleryüz et al., 2020). Some of the programmes that can be used in coding and robotics education in STEM classrooms are given in Table 4.

Table 4. *Programmes that can be used in Coding and Robotics Education in STEM Classrooms*

Age group	Programme	Features	Robot
4+	Code.org	It aims to teach children the basics of coding. In this platform with an object-oriented programming infrastructure, coding levels progress from simple to difficult.	Dash and Dot BeeBot
	Lightbot	It is an application that teaches coding, logic, and problem-solving skills to children by playing games. Children try to complete certain tasks by directing the character.	
5+	Tynker	It can start with block-based coding and progress to writing code in languages such as Python and JavaScript. It allows children to develop problem-solving skills and use their creativity.	Ozobot Dash and Dot Cubelets Sphere 2.0
8+	Scratch	It is coding in the form of blocks, also known as robotic coding education. It allows children to create their own interactive games and animations.	mBot
4-10	Kodable	It is designed for preschool to primary school. It adopts a game-based learning approach.	
10+	Hopscotch	It allows children to design their own projects with its drag-and-drop interface.	Nao
7-12	Lego Education	It is a coding set designed for children aged 7-12.	WeDo 2.0 PLEO rb

It is a fact that coding and robotics represent the future of technology in many work environments, and this trend will increase in the future. In short, coding and robotics will be important for anyone who wants to work in the future, and science, technology, engineering and mathematics courses should prepare students for the world. In order for students to compete nationally and internationally, coding and robotics should be emphasized in the STEM classroom (Bender, 2017). Children who gain coding and robotics skills from an early age start one step ahead to compete, produce creative ideas, and develop practical solutions in our world where these technologies are now completely designed (Karataş, 2021).

Animations and STEM

Another one of the technologies that can be used in STEM classrooms is animations. Especially in the distance education process during the pandemic period, students and teachers participated in the teaching process from different places. This necessitated the use of digital learning tools such as interactive videos, online courses and tests, audio and visual materials in the teaching process. Animations are among the tools that make the learning process less boring in the distance learning process and contribute to more meaningful learning by focusing the student's attention on the lesson.

Animation is a design that shows non-moving pictures or drawings as moving (Wells, 1998). For a design to be an animation, it must evoke a sense of movement in the viewer (Cavalier & Chomet, 2011). Animations should be considered as a universal language that reaches almost all students, including low-achieving students or other students with different backgrounds, languages, or academic strengths (Bender, 2017).

Animated videos are an effective tool to attract students' attention, help them focus, and facilitate their understanding of the material presented by the teacher. Dynamic and interactive educational content presented in various formats can motivate students to participate more deeply in the learning process (Wardani et al., 2024). Thanks to software applications using animation techniques, abstract concepts that are intended to be conveyed to students can be concretized and animated in the mind, eliminating learning difficulties and increasing interaction in the learning process (Karaşahinoğlu, 2013). With animations, a more efficient process can be achieved by focusing the student's attention on the lesson with both a scenario and moving characters used (Aydıngüler & Nalbantoğlu, 2024). Animation can revitalize boring subjects by including movement, depicting processes over time, and showing relationships, as well as focusing concentration and ensuring that the content remains in memory (Bender, 2017).

The ability of animated videos to visualize complex concepts and make them more accessible to students is a key advantage of using this medium in education (Wardani et al., 2024). Animations are not only attention-grabbing things that bring the content to life, but animated cartoon characters are found in almost every subject and can improve long-term memory (Bender, 2017). Moving visuals and animations of concepts or subjects can enhance the learning experience (Lowe, 2003). The use of animations in educational settings greatly influences how students feel about the course and their success in academics (Powell et al., 2003).

Although educators have recognized the importance of interactive visualization tools such as web animations, due to a lack of resources, animations are not widely used in teaching STEM courses (Heinz & Xu, 2012). In fact, allowing students to learn through animation reduces the intimidating aspect of the STEM classroom and provides a way to learn in a non-threatening environment (Bender, 2017). In his research regarding STEM education, Ceylan (2014) found that various approaches and strategies employed in technology fields, including gradual animation methods, teamwork, and the engineering design process, enhance students' abilities in scientific creativity. However, many teachers reported that when students can express themselves creatively through animation in STEM lessons, they are more interested in the lesson and remember more content material (Bender, 2017). Materials that use AR and animation assist learners in seeing, testing, and gathering information on STEM subjects. They allow students to apply their knowledge and utilize computers equipped with specific software like simulations and animations (Lantz, 2009).

Bender (2017) made some suggestions about how teachers can use animation in STEM classes:

- Animations can be used to help classroom management. Some animation websites provide teachers with a variety of teaching options. For example, in Voki (www.voki.com), teachers can draft an assignment on the website for students to complete. Once the students have completed the assignment with their avatar, the teacher can go online, access the avatar, and evaluate the work. Teachers can manage several different classes in the account, as well as different lessons and assignments.

- Animation can be used to teach scientific processes. Various scientific processes are best illustrated by movement over time. Therefore, animations can be important in understanding planetary rotation, life cycles, solar energy harvesting, lunar phases, erosion, or genetic processes. Animations can facilitate understanding of these processes.

- Animations can be used to teach patterns and relationships in mathematics. Various mathematical concepts, skip counting (such as counting by 5, 10, etc.), the relationship between addition and multiplication, or the creation of algorithms can be shown with animations. In this sense, animation can be useful for in-depth learning in mathematics and teaching relationships.

- Avatars can be used for proofreading. Students can check their essays and reports by having their avatars read them. As students hear their avatars speak, they can read together, and this joint reading process makes errors more obvious. Students can make corrections to their work based on the avatar's speech.

- Use introductory avatars. In the lower grades, students can create an avatar that introduces them to their classmates at the beginning of the year and continue to use this digital self throughout the year. This can help introverted or shy students and can sometimes make the first days of school easier

- Avatars can be used for reading. Some students are reluctant to read in front of the class or to read their own written assignments, such as poems or stories. Avatars can be used to do such assignments and alleviate this problem. It will also help struggling readers who can practice getting the audio recording for the avatar exactly right several times before the class reading.

- Animation can be used to develop automatism with mathematical facts. Teachers can encourage students to repeat mathematical facts using their avatars. These repetitions can be uploaded to a class wiki so that the whole class has a bank of facts to use as a study guide. Students can also use their avatars to explain the tips and tricks they know for their numbers.
- Avatars can be used to represent scientists or historical figures. Students can choose a historical figure and create an avatar representing this figure to explain why this historical figure behaves in a certain way. For example, Pythagoras' theorem can explain his theorem in the classroom, and different perspectives can be discussed in the classroom.

Animation tools that can be preferred in STEM classrooms

Powtoon: It is an online animation software that allows users to easily create animated tutorial videos and visually appealing content (Anam, 2019). The Powtoon tool allows us to create cartoons, short videos, and presentations using speech bubbles, shapes, pictures, characters, and many similar materials (Aktaş & Koç, 2022). Its interface is similar to PowerPoint, but it is more vivid and interesting than PowerPoint and usually includes Flash animations (Fitriyani, 2019). The interactive nature of Powtoon videos, coupled with the STEM approach, allows students to explore and apply scientific concepts in a way that is both meaningful and fun (Anam, 2019). Users can prepare impressive content using ready-made templates for free.

Plotagon: It is a Web 2.0 tool where users can prepare original short or long animations interactively based on text or audio. In the field of education, it is a free application that offers users the opportunity to prepare instructive, creative animations very easily, thanks to its ready-made template interfaces (Tekin, 2021). In other words, it allows teachers and students to create 3D animated videos by simply writing a script (Sari et al., 2024). In this way, the user can create his/her own character, set his/her own scene selections, determine his/her own speech texts, voice the script he/she has prepared and add it to the characters, check whether the prepared texts are voiced correctly by the characters, and add gestures and mimics to the character in accordance with the text he/she has written (Tekin, 2021).

Voki: Voki, a tool that allows users to create personalized speaking characters, offers a fun, free, and interactive method to improve speaking skills through a variety of classroom topics and assessments, along with 3-minute challenge activities (Manidaki & Zafiri, 2021). Voki provides multiple methods for recording, including using a microphone or adding audio files. Educators can take advantage of these tools to share their lessons or start discussions, while learners can utilize Voki to hone abilities that might be hard to communicate in a regular classroom environment (İstifanoğlu, 2020). Voki can also be used for role-playing exercises. For example, students can assume the roles of journalists, interviewing their avatars about important events or achievements. This task encourages critical thinking and provides the opportunity to formulate questions and make appropriate recordings in spoken interactions (Panchenko, 2024). It gives students the flexibility to work on and enhance their speaking abilities whenever they want and from any location, extending beyond traditional classroom limits. VOKI speaking avatars are seen as helpful resources in the classroom, enabling different types of presentations and assisting learners in boosting their online speaking skills (İstifanoğlu, 2020).

GoAnimate: It is an online platform that allows users to create animations using themes equipped with backgrounds, characters, and accessories; users can start from scratch, choose a background, and drag and drop backgrounds, characters, and accessories from menus available on the side (Stratton, et. al, 2014). This text-to-video conversion tool gives individuals the flexibility to design an unlimited number of videos according to their needs (Al Khalili, 2018). While some features are commercial, it also has many free features for non-commercial use.

Games, simulations, and STEM

Although games change over time, they have a history as old as human history. Games have an important function in cognitive development (Piaget, 1999). Games are fun, exciting, and immersive activities (Papastergiou, 2009).

Developments in technology have led to changes in both the purpose and types of games. One of these changes is digital games, which have largely replaced classical games today. Digital games are creations made using different technologies that allow players to immerse themselves in a visual setting (Çetin, 2013). Digital game technologies are used as real event simulations in our lives that use the entertainment understanding of classical games as a tool, aiming to direct and train players in line with certain goals (Bülbül, 2022). The fact that digital games are rapidly entering our lives and gaining a bigger place shows significant effects on both children and adults. Digital game is an important phenomenon that provides an opportunity to experience life as well as having fun, increases one's creativity and strategic thinking skills, allows users to use and develop skills such as analysis, decision-making and planning in a virtual environment, supports intellectual and spiritual development, habits and character, and enables socialization (Bülbül, 2022).

Rapid developments in digital games cause children to spend most of their days in the virtual world (Erboy & Vural, 2010). This causes some negative effects as well as positive effects. Excessive and uncontrolled digital games negatively affect individuals, especially children. It can cause many negativities such as deterioration in family relations, decrease in academic success and failure, violent tendencies, addiction, weight gain due to prolonged sedentary sitting, deterioration in back physiology, various eye disorders (Bülbül, 2022). However, although children are reluctant to study, their willingness to play digital games is remarkable (Horzum, 2011).

In many STEM classrooms around the world, games and simulations have become an increasingly important component (Bender, 2017). Several reasons to incorporate digital games into the classroom include grabbing students' attention, keeping their motivation and interest alive, offering engaging visual material, reducing the time needed for learning, and promoting significant understanding (Doğusoy & İnal, 2006). Digital educational games for STEM education are considered to provide interactive and engaging learning environments that help students develop their STEM-related knowledge and skills (Gui et. al., 2023). A game-based STEM learning environment can be seen as a virtual application that provides students with a learning context, guidelines that support discovery, and opportunities to collaborate (Klopfer & Tompson, 2020).

The National Science Foundation indicates that games focused on STEM subjects have emerged as a novel approach to education in K-12 settings and serve as effective resources for teaching STEM fields (National Science Foundation [NSF], 2008). In fact, since 2010, educational games have become a viable STEM teaching strategy (Bender, 2017). Moreover, researchers have indicated that digital games can achieve diversified STEM learning goals that increase students' motivation to learn, enhance their understanding of knowledge concepts, and improve their problem-solving abilities (Hwang et. al., 2012).

Bender (2017) made some suggestions for teachers who want to use games in STEM classes:

- *Start with what you know*. Teachers who have never played educational games before should carefully select one or two websites that provide simpler, stand-alone games that focus on specific teaching content. Many of these games are highly engaging and can be used the day after initial teacher exploration.
- *Match virtual worlds with your content and instructional purpose.* When selecting games for STEM education, the game content should be aligned with the learning programme. It is important that the game is created for educational purposes. Games developed for entertainment purposes are not appropriate. Games with richer and deeper content that will maximise learning in STEM classes should be preferred.
- *Preview the game.* Teachers should always play any game they choose to use in the classroom at least once before the lesson. This allows teachers to determine the use of the game and to establish levels of play for children at different academic levels.
- *Relate game themes to non-game content.* The game becomes much more effective when the relationship between game content and activities and teaching content is clearly emphasised. Students learn while playing. The teacher's role in this process is to show students the relationship between the subject matter and the game content.

- *Teach digital citizenship.* Educational games and virtual worlds can be unsafe online environments. Therefore, teachers should inform students about cyber security and safe use of the internet. In the near future, games will be an important part of STEM education. Therefore, student safety should always be the most important element.
- *Do not limit the use of games.* Students can perform differently with educational games and virtual reality. Therefore, teachers should be careful not to limit this. Assignments should be given in game format with general criteria without killing opportunities for students to develop their creativity.
- *Play, Test and Repeat.* In the last stage, the teacher should assign a few students to play the game. After playing the game, the students should report on the game. This report tests whether the students have grasped the content correctly. If the content is not grasped well enough, the teacher can give the game again.

Virtual reality, augmented reality and STEM

The use of technological tools in STEM education helps the education process to become more meaningful by concretizing abstract information. Complex structures and experimental environments that are difficult to observe are more accessible in the classroom environment thanks to technology. Especially virtual reality (VR) and its derivative systems offer a new educational experience free from the monotony and limitations of traditional educational practices.

The development of technology has not only increased its qualities but also made it more accessible. Virtual reality and augmented reality technology has started to reach users from all walks of life with the development of mobile devices. While this spread has advantages, it has also caused conceptual misconceptions among users. Defining virtual reality and its derivatives is important in this respect.

Virtual reality is an application in which the user is completely involved in a computer-generated interactive digital environment by leaving the real environment (Sherman & Craig, 2018). The environment created by virtual reality for its users consists entirely of a digital environment. The effectiveness of applications that can appeal to all senses of the user and make them feel as a part of the digital environment he is in is at a high level. Using hardware that will make the individuals using the virtual reality application feel the conditions of the environment they are in in the digital environment and manipulate their perceptions will increase the sense of immersion of the application, and at the same time, cognitively immerse the user. Providing this experience makes this application more burdensome in terms of both hardware and software. As hardware, there are various tools used to realize virtual reality applications. Some of these tools are presented in Table 5.

Table 5. *Tools that can be used to Realize Virtual Reality Applications in STEM Classrooms, Purposes of Use, and Features*

Hardware	Task / Intended Use	Features
VR Headset	Allows you to see the virtual world	Display in front of the eyes, 3D image, wide viewing angle, eye tracking
Control Devices	Interaction with the virtual environment, detection of hand gestures	Joystick, buttons, touchpad, motion sensors
Computer / Console / VR Device	Runs the application, provides graphics, and processing power	High-performance CPU and GPU, VR-compatible systems
Motion Tracking Systems	Detects the user's position and movements	In-header or external sensor systems
Sound Systems	Provides realism with 3D sound	Head-mounted or external, positioned sound systems
Haptic Gloves / Feedback	Increases interaction with the sense of touch	Vibration, pressure, and force feedback
Walking Platforms	Enables physical movements to be transferred to the virtual environment	Walk/run tracking

Augmented reality is an application that allows user interaction by displaying three-dimensional virtual elements in a real environment (Azuma, 1997). The main feature that distinguishes augmented reality from virtual reality is that it adds three-dimensional elements to the real environment rather than creating a completely artificial environment for its users. This application, which can be used with everyday technological devices, makes it more accessible compared to virtual reality. The "view the product in three dimensions" option, frequently found on shopping websites or three-dimensional image filters in social media applications, can be shown as example of augmented reality applications. As in virtual reality technology, there are various hardware components in augmented reality technology where applications can be used. Examples of this hardware are presented in Table 6 with their usage purposes and features.

Table 6. *Tools that can be used to Realize Augmented Reality Applications in STEM Classrooms, Purposes of Use, and Features*

Hardware	Task / Intended Use	Features
AR Goggles / Headgear	Overlays virtual objects on the real environment	Transparent screen, sensors, camera, lightweight design
Mobile Devices (Phone / Tablet)	Runs AR applications	Camera, GPS, accelerometer, ARKit / ARCore support
Camera and Sensors	Recognize the environment and position digital elements correctly	Depth sensor, LIDAR, motion sensors
Processor / Computer / Cloud Systems	Processes and presents AR content	High processing power, low latency, and remote data processing
Sound Systems	Provides real-time audio feedback	Microphone, headset, and positional audio technologies
Handheld Control Devices	Provides physical interaction with AR	Buttons, motion sensors, touchpad
Wearable Technologies	Enriches the AR experience with complementary data	Smartwatch, wristband, haptic feedback

Virtual reality and augmented reality applications offer a teaching environment in which both teachers and students can actively participate by stretching the boundaries drawn by traditional education. These applications are considered an important opportunity to increase the effectiveness of learning, especially in courses such as science, where experimentation and observation are at the forefront.

Virtual reality and augmented reality applications are auxiliary resources that attract students' attention and increase their interest and curiosity towards the lesson. Students can realise their observations by not hesitating to make mistakes in the virtual experiment environment.

Virtual reality and augmented reality applications help students to make sense of abstract content that causes misconceptions more easily by making it concrete. Applications such as three-dimensional modelling of cells, annual movements of the Earth can be given as examples.

Virtual reality and augmented reality applications can model experiences that users do not have the opportunity to experience in real life. Thanks to the artificial environment created by virtual reality, students can be a guest of a space station, closely examine the working principle of a nuclear reactor, or observe the parts of the human organism in detail. Such experiences support students to learn by doing and living, and contribute to them take a more active role in the learning process.

Virtual reality and augmented reality applications can also be prepared by students. Simulations, three-dimensional objects, interactive environments to be used in the lessons can be designed by students and provide them with the opportunity to develop cognitive skills such as problem solving and co-operation. In Table 7 below, examples of applications that can be used in STEM classrooms are presented.

Table 7. *Virtual and Augmented Reality Applications that can be Used by Students in STEM Classrooms*

Application Name	Type	Area of Use	Properties / Description
Google Expeditions	VR / AR	Virtual field trips, science	Takes students to different scientific environments with virtual tours, 3D object, and structure examination
Merge EDU	AR	Science, space	AR learning of topics such as cells, molecules, planets with 3D models
Human Anatomy VR	VR	Biology, anatomy	Examination of the human body in 3D, interactive systems
InMind VR	VR	Nervous system, biology	Nervous system education by observing neurons in the brain
Froggipedia	AR	Biology, anatomy	Virtual examination and dissection of frog anatomy with AR
Star Chart	AR	Astronomy	Watching the sky in real time, learning about stars and planets
Anatomyou VR	VR	Human body systems	A virtual tour through systems such as respiration and circulation
Curiscope Virtuali-Tee	AR	Biology, anatomy	Visualization of internal organs of the human body with an AR T-shirt and a mobile device
JigSpace	AR	General science	Learning molecules, machines, and scientific processes with 3D and AR
BioDigital Human	AR / Web	Anatomy, health	Interactive 3D exploration and learning of human body structures

Although the use of virtual reality and augmented reality applications offers unique opportunities to the educational environment, it also has limitations. Especially in virtual reality applications, the need for extra hardware increases the cost. The necessary technical infrastructure should be provided during the application, and the readiness of users and developers about technology should not be ignored. The prepared contents should be suitable for the pedagogical level of the users. The feeling of immersion provided by the applications should not cause negative emotions in the student.

Artificial intelligence and STEM

Artificial intelligence has assumed a transformative role in education, as in all fields. From the first steps of this technological development, it was thought that it could provide individual educational environments more easily, measure student development more accurately, and provide teachers with the opportunity to carry out process follow-up more functionally (Luckin & Holmes, 2016; Woolf, 1991).

One of the strongest pillars of STEM education is life itself. The main goals of STEM education are to produce solutions to the problems encountered in daily life and to ensure the adaptation of human beings to their environment and today's world. Thanks to STEM education, students perceive the problem holistically and produce a solution to their problems by using all disciplines. In this respect, STEM education is recommended as a teaching method that serves equal opportunity in education by ensuring that all students are involved in the process (Kricorian et al., 2020). At the same time, this method, which makes the fields of science, mathematics, engineering, and technology holistically present in the process, serves to recognize these fields of science. Students who apply it are more likely to make career plans in STEM fields.

Recent developments in data analytics and artificial intelligence have led to the need to review many factors in education. While the world endeavors to raise individuals who will think in multiple ways, today it is faced with a power that can evaluate many events from different aspects and even reveal their possible relationships with each other. This situation has proved that traditional teaching methods should be shelved much faster. Now, instead of memorizing the structural elements of a cell, students questioning what kind of structure the cell requires for an artificial organ can sustain its life activities will take mankind one step further.

It is believed that the strategic integration of artificial intelligence will provide great potential power for the development of STEM education (Triplett, 2023). In particular, artificial intelligence can provide high support for personalized learning. With the data records that can be created separately for each student, the detection and support of students with missing gains can be created much more clearly.

For teachers, it can be used as a facilitator in the planning and evaluation stages. The ability to stage the teaching according to the individual characteristics of the students (easy-difficult), to produce different scenarios in defining the problems by associating with daily life, to follow the evaluation data for each student and to identify the deficiencies will greatly alleviate the workload of the teachers (Nuangchalerm & Prachagool, 2023).

The deficiencies that students experience in technical issues during STEM education applications can be overcome thanks to artificial intelligence. If the child who has a solution proposal for the problem he/she encounters feels deficient in the ways in which he/she can do this, he/she can benefit from artificial intelligence and see different effects. For example, a student who imagines that he works as a paleontologist may think that he needs to protect the fossil against weather conditions while thinking about the factors that will facilitate his work in the field on the fossil. The child who thinks of designing an opening and closing system for the fossil can imagine that the automation system of this system will be operational even when no one is in the field. He can research the issues that can provide this through artificial intelligence and add wind and rain sensors to his system. Even if he does not have intensive training on coding, he can ensure the operation of these sensors through artificial intelligence. By introducing the problem and solution proposal to artificial intelligence, it can make alternative situations, possible risks, and financial analyses. Artificial intelligence can be used as a structure that provides feedback for students, supports and facilitates their progress, and positively affects their motivation. Students who receive technology support without getting stuck in details and difficulties can use their innovative thinking power to find alternatives. They can catch different excitements and support career development. In this respect, artificial intelligence is a tool that can be frequently used in STEM education. In Table 8 below, frequently used artificial intelligence tools and some examples of how they can be utilized at which stage of STEM education are listed.

Table 8. Commonly Used Artificial Intelligence Tools and Their Use in STEM Education

Artificial Intelligence Application	STEM education phase, in which it can be used	Benefits
Khanmigo (Khan Academy AI)	Learning Process / Interactive Education	It guides the students by explaining the subjects step by step and helps them in solving questions.
ChatGPT / Teacher Assistant	Question and Answer, Homework Support	It answers students' questions instantly, helps them to do research, and write assignments.
Socratic (Google AI)	Out of Class Support / Individual Study	Shows the solution to the problem by taking a photo with the phone; especially useful in maths and science lessons.
Google Classroom + AI integrations	Classroom Management / Feedback	It tracks student progress, provides automatic assessment, and personalised feedback.
Labster (Virtual Laboratory)	Hands-on Experience / Simulations	It offers students the opportunity to perform biology, chemistry, and physics experiments in a virtual environment.
Teachable Machine (Google)	Project-Based Learning / Coding	Students can easily create their own artificial intelligence models.
Scratch + AI extensions	Early Age Coding Education	It teaches AI concepts with a simple interface, especially at the primary and secondary school levels.
MATHia (Carnegie Learning)	Maths Teaching	Offers student-specific exercises and adaptive assessment.
DeepL	Inclusion and Accessibility	Provides equal opportunities for students who speak different languages by translating materials into their mother tongue.

Elicit	Scientific Research and Literature Review	Provides answers to students' research questions supported by academic articles.
Notion AI	Note Taking, Project Planning	Assists in planning, researching summarizing, and preparing written presentations for STEM projects.
Quillionz	Preparing teacher evaluation questions	Generates automatic multiple-choice questions and quizzes from subject texts.
Zygote Body (former Google Body)	Biology / Human Anatomy	Provides interactive learning with a 3D human body model.
Edmentum Exact Path	Personal Learning Plan	Offers personalized STEM education pathways based on students' test results.
AI Dungeon (Educational adaptation)	Creativity and Scenario Simulation	Interactive scenarios can be created for coding or engineering problems.

It should not be forgotten that artificial intelligence should be used as a tool for teaching. Otherwise, ethical violations may arise. When the student uses it outside its purpose, he/she may get used to readiness. It should be taught that plagiarism is an ethical violation, and the area of use should be limited accordingly. If students use artificial intelligence more than necessary, the development of creative thinking skills may be hindered. They may stop thinking critically and progress with the support of artificial intelligence without questioning (Nguyen et al., 2023). The support received from artificial intelligence during the monitoring and evaluation of learning processes may be another ethical violation situation when students' personal data becomes widely accessible. Teachers and school administrators should pay attention to this situation and protect personal data. Although the use of artificial intelligence in education contributes to the learning and teaching process, it should not be forgotten that human education should not be completely handed over to artificial intelligence, which is machine learning.

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PROSPECTIVE MATHEMATICS TEACHERS' VIEWS ON ARTIFICIAL INTELLIGENCE SUPPORTED ACTIVITY PREPARATION PROCESS

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Introduction

In recent years, rapid developments in information and communication technologies have profoundly transformed the structure of education systems and artificial intelligence is at the centre of this transformation. With these technological developments, changes in teaching processes also attract attention (Akgün, 2019). Many pedagogical innovations such as digitalisation of teaching processes, enrichment of learning environments and adoption of student-centred approaches can be implemented more effectively with artificial intelligence applications. Artificial intelligence, which supports the fulfilment of human tasks, also turns into an educational technology that facilitates teachers' work in many areas such as content production, student evaluation, course planning, individualised instruction (Akkol & Balkan, 2024). Artificial intelligence applications, which offer individualised learning opportunities especially in educational environments and enable the creation of teaching materials quickly and flexibly, restructure teaching and learning processes (Demircioğlu, Yazıcı & Demir, 2024).

Due to the Covid-19 pandemic, digital technologies and artificial intelligence-based platforms have been widely used in our country and in the world. In this process, artificial intelligence aims to increase student success by providing content according to students' learning pace and interests and differentiating from traditional methods (Bilgin, 2021). Of course, the widespread use of artificial intelligence technologies was not limited to the pandemic period, and these technologies continued to take a permanent place in education. In this context, thanks to the artificial intelligence-based technologies used by the Ministry of National Education within the scope of digitalisation policies, students in various regions of Türkiye have easy access to resources, thus ensuring equality of opportunity in education (Aydın, 2021). One of these technologies, the artificial intelligence-based Education Information Network (EIN) platform offers support to both students and teachers (Bilgin, 2021).

Mathematics education includes various cognitive activities such as understanding abstract concepts, developing analytical thinking skills and structuring problem solving processes. In this context, artificial intelligence offers new learning and teaching opportunities for both students and teachers in mathematics teaching (Akkol & Balkan, 2024).

In particular, generative artificial intelligence applications such as ChatGPT allow teachers to design classroom activities in shorter time, more diverse and creative ways. These tools facilitate teachers' time management, help to personalise teaching materials and offer flexibility to respond more quickly to student needs (Dumlu, Gezer & Yıldız, 2024). However, this potential of artificial intelligence in education brings along various responsibilities and questions. It is especially important that teachers consider artificial intelligence not only as a technology but also as a pedagogical support and tend to use it in their courses. Because the most important factors that increase the efficiency of artificial intelligence supported content are the teacher's pedagogical knowledge, critical evaluation skills, and thoughts about using artificial intelligence. In this context, the thoughts and experiences of teachers who will become more qualified by using artificial intelligence in their courses reveal to what extent they have internalized this technology, which aspects they find functional and the limitations they face (Demircioğlu, Yazıcı, & Demir, 2024). Therefore, an in-depth examination of teachers' experiences and views on activities prepared with artificial intelligence is a critical need for the effective, ethical and pedagogical integration of these tools into teaching processes.

In the literature, the use of artificial intelligence in education is addressed in aspects such as preparing teaching materials, analysing students' individual learning levels, personalising teaching processes and designing interactive learning environments (Demircioğlu, Yazıcı & Demir, 2024). In mathematics teaching, these tools are especially used to concretise abstract concepts, support students' learning at different paces and levels, and facilitate teachers' activity production processes (Akkol & Balkan, 2024). However, in recent years, it is also seen that there have been studies on the preparation of mathematical activities and course plans. For example, Dertli and Yıldız (2025) examined the results of different inputs and prompt engineering in the process of designing a mathematical modelling activity using ChatGPT. In Dumlu, Gezer, and Yıldız's (2024) study, the examination of course plans prepared with ChatGPT-3.5 and 4 models showed that artificial intelligence can assume the role of a teaching assistant for teachers. However, in the same study, it was emphasised that teachers should review pedagogical compatibility and content accuracy when using these tools. As a matter of fact, it is stated that the direct application of the content created by generative artificial intelligence systems may be problematic and that the guidance of the educator is essential, especially in terms of pedagogical accuracy (Demircioğlu, Yazıcı & Demir, 2024).

Some studies reveal that teachers see artificial intelligence tools as a time saving, innovative and differentiating resource in the production of course activities; however, they are hesitant about issues such as technological infrastructure, ethical concerns and content accuracy (Akkol & Balkan, 2024). This situation shows that teachers should have artificial intelligence literacy not only in technical but also in pedagogical, ethical and cognitive dimensions. Mathematics teachers' attitudes towards artificial intelligence supported activities directly affect student achievement, the diversity of teaching methods and the richness of learning environments.. For this reason, research to understand teachers' experiences, expectations and criticisms will make significant contributions to the more conscious and efficient use of artificial intelligence applications in education.

The purpose of the research

In this context, the main purpose of the research is to determine the views of prospective mathematics teachers on the process of preparing activities using artificial intelligence. In this direction, in this study, answers to the following sub-problems were sought in order to determine the views of prospective mathematics teachers about their experiences in the process of preparing activities using artificial intelligence, the difficulties they encountered, and the gains they achieved:

1) What are the factors that prospective teachers pay attention to when preparing activities with artificial intelligence?

2) What are the situations that prospective teachers have difficulty in preparing activities with artificial intelligence?

3) What are the contributions of the process of preparing activities with artificial intelligence to prospective teachers?

It is thought that the results of this study will provide important clues about the conscious use of artificial intelligence tools, activity design and technology integration in teacher education programmes. It is also expected to contribute to the process of shaping the policies to be developed for artificial intelligence literacy.

Theoretical Framework

Artificial intelligence concept and using in education

Artificial intelligence is defined as the ability of machines to imitate human-like learning, reasoning, problem solving and decision making skills (McCarthy et al., 1955). At the same time, this technology, which has the ability to perceive, comprehend, make sense, generalise, infer and learn, can successfully perform many tasks at the same time (Gondal, 2018). Therefore, it is seen that artificial intelligence and its applications take place in many fields such as energy, health, mining, agriculture, voice assistants, online chat and communication, software development (Arslan, 2020). Of course, one of these areas has been education. The introduction of artificial intelligence into our lives has significantly affected educational services (Popenici & Kerr, 2017). In the field of education, artificial intelligence provides support in areas such as individualisation of learning environments, automation of teaching processes, instant monitoring of student performance and content production for teachers (Demircioğlu, Yazıcı & Demir, 2024). Beyond saving time and labour in education, these technologies have the potential to make the teaching process more effective, flexible and student-oriented (Akkol & Balkan, 2024).

The use of artificial intelligence in education contributes to providing personalized learning experiences, responding quickly to student needs, reducing the routine work of teachers and enriching teaching materials. However, these potential uses bring with them critical issues such as ethical responsibilities, content accuracy and pedagogical appropriateness (Demircioğlu, Yazıcı & Demir, 2024). However, teacher guidance in the use of artificial intelligence remains at the centre of student learning. In order to effectively integrate artificial intelligence technologies into education, teachers should be able to integrate their pedagogical knowledge with the use of technology (Demircioğlu, Yazıcı & Demir, 2024). In addition, how teachers perceive artificial intelligence and what kind of advantages and limitations they see are directly effective on the dissemination and effective use of this technology (Demircioğlu, Yazıcı & Demir, 2024; Akkol & Balkan, 2024). Therefore, teachers' views on the activities they prepare with artificial intelligence have a decisive and critical role in terms of the integration of these technologies into educational environments.

The effect of artificial intelligence on mathematics education

Mathematics education aims to deepen students' conceptual understanding and develop their problem solving and critical thinking skills. Artificial intelligence provides strong support to teachers in achieving these goals (Akkol & Balkan, 2024). Especially in mathematical problem solving processes, artificial intelligence-supported tools encourage creativity by offering different solutions to students and enable teachers to develop more personalised teaching strategies (Dertli, Korkmaz Güler & Yıldız, 2024). In addition, visualisation of abstract mathematical concepts strengthens students' conceptual understanding and makes the learning process more permanent. Due to the similarity in its systematics and structuring, it is seen that mathematics is one of the fields where research on the concept of artificial intelligence is used the most (Holmes, Bialik & Fadel, 2019). When mathematics teaching based on artificial intelligence is organised according to the conditions of the education system, it supports student learning and development (Wu, 2021).

The use of artificial intelligence tools by mathematics teachers while producing in class activities adds both quality and diversity to the teaching process (Dumlu, Gezer & Yıldız, 2024). Generative artificial intelligence systems (especially ChatGPT etc.) not only accelerate teachers' activity preparation processes but also contribute to the enrichment of teaching content by providing original ideas. In this process, teachers can benefit from artificial intelligence in various ways such as creating problems, generating solutions, designing activities appropriate for student level and developing tools to concretise abstract mathematical concepts (Demircioğlu, Yazıcı & Demir, 2024). However, it is not enough for the activities to be technologically correct; they should be pedagogically appropriate to the learning objectives of the students, sensitive to their developmental levels and supportive of learning. In this context, it is of great importance for teachers to critically evaluate the contents produced from artificial intelligence and to edit them when necessary (Demircioğlu, Yazıcı & Demir, 2024).

Method

Research design

This study aims to elucidate prospective mathematics teachers' views on the process of preparing activities using artificial intelligence. The research is a case study conducted within the framework of qualitative research method. A case study provides an opportunity for an in-depth and detailed examination of an event, program or individual in its natural environment (Merriam, 2009).

Study group

In this study, 56 volunteer prospective mathematics teachers studying in the last year of the Mathematics Teacher Education program of a state university and taking a 14-week elective course 'Activity Design in Mathematics Teaching' took part. Participants were selected using convenience sampling (Creswell, 2012). These 56 volunteer prospective mathematics teachers formed 24 groups. Prospective teachers participated in the study in groups formed on a voluntary basis. In order to protect the confidentiality of the participants, codes such as G1, G2, ..., G19, G20, G24 were used for the groups formed.

Data collection tools and data collection

The data were collected face-to-face by preparing a semi-structured interview form. This interview form, which was used as a data collection tool, was prepared by taking the views of two experts experienced in the field. First of all, prospective teachers were informed about how to use artificial intelligence in mathematics teaching and how to communicate. Afterwards, prospective teachers were asked to prepare activities for the common outcome given to them as a group, with the support of artificial intelligence. Prospective teachers were asked to use ChatGPT as an artificial intelligence tool. From the conversations with the prospective teachers, it was determined that they had previously used ChatGPT to help with their homework. The process was completed with different stages such as course process, briefing before the activity design, preparation and design. At the end of this process, their views were collected with a semi-structured interview form prepared about this process. The interview form includes three questions aimed at determining the views of prospective mathematics teachers on the process of preparing activities using artificial intelligence. In this way, it was aimed to obtain the views of the prospective mathematics teachers in detail.

Data analysis

In the study, the answers obtained through the interview form were analyzed by a content analysis method. In the content analysis process, each question was evaluated within itself. Prospective teachers' views on the factors they pay attention to in the process of preparing activities using artificial intelligence were analysed within the scope of the first research sub-problem, and their views on the situations in which they have difficulties were analysed within the scope of the second research sub-problem. Their views on the contributions of this process to themselves were also evaluated within the scope of the third research sub-problem. In the analysis process, the data were first conceptualised and then systematically organised within the framework of these concepts. As a result of the analyses, themes were formed. Each researcher completed the data analyses independently. Then, meetings were held on the consensus and disagreements that emerged during the process. Necessary arrangements were made and consensus was reached on the parts where there was disagreement.

Findings

In this part of the study, firstly, the data obtained from the views of prospective mathematics teachers about the factors they pay attention to when preparing activities with artificial intelligence were analysed. Then, the views of prospective mathematics teachers on the situations in which they had difficulties in preparing activities with artificial intelligence, and finally, the data on the views of prospective mathematics teachers on the contributions of the process of preparing activities with artificial intelligence to them were evaluated together with the analyses performed. In this context, the findings of the study are given.

Prospective mathematics teachers' views on the factors they pay attention to in the process of preparing activities with artificial intelligence

In line with the first sub-problem of the research such as " What are the factors that prospective teachers pay attention to when preparing activities with artificial intelligence?" the views of prospective mathematics teachers on the factors they pay attention to when preparing activities using artificial intelligence were evaluated. The analyses of the answers are presented in Table 1.

Table 1. *Factors That Prospective Teachers Pay Attention to When Preparing Activities with Artificial Intelligence*

Theme	Subtheme	Participant Groups
In the context of the features that the activity should have	Constructivist approach	G1
	Activity design principles	G1, G3, G7, G8, G9, G10, G11, G13, G12, G16, G17, G20, G22, G23
	Appropriateness to student level	G6, G22
	Including high order thinking and process skills	G7, G6
	Being understandable	G7
	Being effective and improvable	G11, G22
	Clarity and understandability in activity guidelines	G16, G22, G24
	Being interesting and entertaining	G7, G9, G11
	Not going out of the outcome	G2, G7, G8, G12, G19, G20, G22
	Being appropriate for the purpose	G4, G10
	Applicability of the activity in the classroom environment	G6, G18
	Consideration of misconceptions	G16, G21
	Student being active	G21
In the context of the use of artificial intelligence	Training of artificial intelligence	G5, G6, G8
	Guidance using descriptive, clear and constructive language	G3, G4, G5, G8, G15, G18, G24, G13
	Using a detailed language	G2, G3, G5, G6, G10, G12, G14

According to the data in Table 1, the answers of prospective mathematics teachers about the elements they pay attention to while preparing activities were divided into two themes: ‘in the context of the features that the activities should have’ and ‘in the context of the use of artificial intelligence’. In the context of the features that the activity should have; constructivist approach, activity design principles, appropriateness to the student level, including high order thinking and process skills, being understandable, being effective and improvable, clarity and understandability in activity guidelines, being interesting and entertaining, not going out of the outcome, being appropriate for the purpose, applicability of the activity in the classroom environment, consideration of misconceptions and students being active sub-themes are included. In this context, it is seen that many different views have emerged. When these views are examined, it can be stated that the design and implementation of the activity were emphasised. It is seen that prospective teachers pay attention to the features that the activity should have and the situations related to the use of artificial intelligence while preparing activities with artificial intelligence. In the context of the features that the activity should have, prospective teachers' views on the points they pay attention to differ. In this context, the most emphasised sub-theme was activity design principles. Then, not going out of the outcome was the other sub-theme emphasised. G7's statement “...the fact that it is an activity does not go out of the outcome framework...” points to this sub-theme. It is seen that the least emphasised sub-themes are constructivist approach (G1), being understandable (G7), student being active (G21). For example, G24's statement “...again, we also paid attention to the understandability of the guidelines of the activity...” emphasises the sub-theme of clarity and understandability in the activity guidelines.

In the context of the use of artificial intelligence; it is seen that the sub-themes of training artificial intelligence, guidance using descriptive, clear and constructive language, and using a detailed language emerged. In the context of the use of artificial intelligence, prospective teachers state that they pay the most attention to using a descriptive, clear and constructive language, guiding artificial intelligence and using a detailed language. For example, G3's statement “We wanted him to pay attention to the use of descriptive and detailed language...” emphasises the use of descriptive language on the one hand and detailed language on the other. Similarly, G15's statement "First of all, we tried to write the outcome we wanted understandably and clearly, we tried to ask the right questions so that the artificial intelligence could make the changes we wanted correctly" also emphasises guiding by using an descriptive, clear language. Apart from the use of language, the emphasis of prospective teachers on the training of artificial intelligence is also noteworthy. The statements of G5 as 'We first trained artificial intelligence...' and G6 as 'We first taught artificial intelligence the basic things related to our subject...' support this sub-theme.

Prospective mathematics teachers' views on the situations they have difficulty in the process of preparing activities with artificial intelligence

In line with the second sub-problem of the research such as "What are the situations that prospective teachers have difficulty in preparing activities with artificial intelligence? analyses and the analyses of the answers are presented in Table 2.

Table 2. *Situations in Which Prospective Teachers Have Difficulties While Preparing Activities with Artificial Intelligence*

Theme	Subtheme	Participant Groups
Difficulties in revising the activities given by artificial intelligence	Concretising the activity	G1
	Making the activity appropriate to the principles of design	G1
	Editing the prepared activities	G9
Difficulties in the effectiveness of the activity ideas given by artificial intelligence	Creating activity suggestions superficially	G4, G7, G10, G15, G16, G22, G23
	Inability to prepare creative activities	G8
	Delay in visual creation	G11
	Not appropriate for student level	G13
Difficulties in using artificial intelligence	Not providing the desired answers and applications	G2, G3, G4, G6, G7, G10, G12, G13, G14, G15, G17, G18, G20, G21, G22
	Difficulty in communicating	G4, G8, G17, G18, G14, G12
	Message limitation, limit expiry	G4, G5, G6, G7, G11, G13, G12, G16, G21, G22
	Long time to train artificial intelligence	G5
	Receiving continuous feedback	G24

According to Table 2, the views of prospective teachers about the difficulties experienced in the process of preparing activities with artificial intelligence were grouped under three different themes: the difficulties experienced in revising the activities given by artificial intelligence, the difficulties experienced in the effectiveness of the activity ideas given by artificial intelligence and the difficulties experienced in using artificial intelligence. While expressing the difficulties experienced in using artificial intelligence, it is seen that a large number of prospective teachers emphasised that it does not provide the desired answers and applications, message limitation, limit expiration and difficulties in communicating. It is noteworthy that there is one group that states that they have difficulties in training artificial intelligence and receiving continuous feedback. For example, G2's statement "Artificial intelligence does not give the answers to the questions asked exactly as we want..." and G20's statement '...although we clearly expressed our requests during the activity improvement process, we could not get the results we wanted very much.' point to the difficulties experienced in terms of not being able to provide the desired answers and applications.

G14's statement that "...at the point where we wanted him to offer different alternatives, he could not offer us very different innovative ideas and we had to give more and detailed guidance." points to both the difficulty experienced in communication and the inability to get the desired answers. It is seen that the G21 group emphasised the difficulties experienced in terms of limit expiry with the statement '...if you go with corrections, our limit expires, especially when we want to create a visual'.

The prospective teachers stated that the difficulties in the effectiveness of the activity ideas given by artificial intelligence are that artificial intelligence delays in creating visuals, creates activity suggestions superficially, unable to create creative activities, and the activities are not appropriate for the student level. For example, G4's statement "...We had difficulty because he thought the activities superficially." and G16's statement '...Firstly, it prepared a very superficial activity and elaborated as we gave the commands...' point to the difficulties arising from the superficial creation of the activities. The statement '...Also, we waited a lot while creating the visuals.' of the G11 group indicates the difficulties experienced in creating the visuals.

Finally, the difficulties in revising the activities given by artificial intelligence were stated as concretising the activity, making it appropriate to the principles of activity design, and editing the prepared activity. For example, G1's statement "...We had difficulty in concretising the activity..." points to the difficulties experienced in concretisation, and

G9’s statement ‘...We had difficulty in editing the activity prepared by artificial intelligence’ points to the difficulties experienced in editing.

Prospective mathematics teachers' views on the contributions to them of the process of preparing activities with artificial intelligence

In line with the third sub-problem of the research such as “ What are the contributions of the process of preparing activities with artificial intelligence to prospective teachers?” analyses and the analyses of the answers are presented in Table 3.

Table 3. *Contributions of the Activity Preparation Process with Artificial İntelligence to Prospective Teachers*

Theme	Subtheme	Participant Groups
Having knowledge about artificial intelligence	Using artificial intelligence effectively and efficiently	G1, G8, G12, G16, G19
	Communicating with artificial intelligence	G2, G22
	Asking questions to artificial intelligence	G3, G13
	Guiding artificial intelligence	G3
Self improvement	Gaining a different perspective	G1, G12, G20
	Acquiring different knowledge and ideas	G4, G13, G15, G23, G18
	Creating effective visuals	G6
	Gaining the ability to criticise	G12
	Contribution to professional life	G9, G11, G16
	Creating an activity draft	G14
	Reinforcing the principles of activity design	G23
	Time saving	G4, G5, G6, G9, G10, G15, G17
No contribution		G7

In Table 3, the views of prospective mathematics teachers about the contributions of the process of preparing activities with artificial intelligence to them are analysed. It was seen that the answers obtained were categorised under the themes of having knowledge about artificial intelligence, self improvement and no contribution. All groups except G7, who stated that this process did not make any contribution to them, expressed positive views. Prospective teachers expressed the contributions of the process to them in terms of having knowledge about artificial intelligence as using artificial intelligence effectively and efficiently, communicating with artificial intelligence, asking questions to artificial intelligence and guiding artificial intelligence. 'It was useful for question asking skills (asking appropriate questions). It contributes to the ability to guide. It was able to present different ideas to us.' indicates that it contributed to asking questions to artificial intelligence and guiding artificial intelligence.. For example, G2's statement '...We learnt how to talk with artificial intelligence. We learnt to explain in detail while talking.' supports the sub-theme of communicating with artificial intelligence. G19's statement "It contributed to my better use of artificial intelligence..." and G16's statement 'I learnt to use artificial intelligence better and more efficiently in my life...' emphasise the effective and efficient use of artificial intelligence.

The prospective teachers expressed the contributions of this process to their self improvement as gaining a different perspective, acquiring different knowledge and ideas, creating effective visuals, gaining the ability to criticise, contributing to professional life, creating an activity draft, reinforcing the principles of activity design, and time saving. It is noteworthy that the contribution in terms of time saving is emphasised the most. For example, G4's statement "We saved time and completed the activity in a shorter time..." and G6's statement 'It saved time in terms of timing....' point to the contribution of time saving. G15's statement "...made good activity suggestions that we had not thought of." also emphasises the contribution in terms of acquiring different knowledge and ideas. The statement of G6 group '...Created effective visuals.' supports the sub-theme of creating effective visuals. G11's statement "It inspired us for our future professional life..." and G16's statement '...we saw that it would be very useful when we started our professional life.' point to the contribution of the process to professional life.

Conclusion, Discussion and Suggestions

In this study, the views of prospective mathematics teachers on the process of preparing activities using artificial intelligence are examined. In this context, the main purpose of the research is to obtain in-depth information about the experiences of prospective mathematics teachers in the process of preparing activities using artificial intelligence, the difficulties they face, and their views on the gains they have achieved. The findings obtained provide important insights on the conscious use of artificial intelligence tools, activity design and technology integration in teacher education programmes.

Within the scope of the issues they pay attention to while preparing activities with artificial intelligence, it was concluded that prospective mathematics teachers focused on the features that the activity should have and the situations related to the use of artificial intelligence. In the context of the use of artificial intelligence, the most emphasis was placed on the use of descriptive, clear and constructive language, guidance and detailed language. This shows that prospective teachers are aware of the importance of communication with artificial intelligence. Emphasising that they need to give correct and descriptive commands in order to get efficient results from artificial intelligence expresses that they take responsibility and accept that they are the ones who manage the process. In the study by Dwivedi et al. (2023) and Liu & Ma (2023), it is pointed out that it has become important to train students on how to use artificial intelligence effectively. This situation supports the results of this study. It is important to train not only students but also teachers and prospective teachers. As a matter of fact, Özdemir-Baki (2024) also stated that in order to carry out an artificial intelligence-based education in mathematics classrooms, teachers should first gain the necessary knowledge and skills. In general, it can be said that prospective teachers are aware that they can create effective and efficient activities by using correct language with artificial intelligence and giving the necessary explanations and information in advance. Tapan Broutın (2023) examined the interaction of prospective mathematics teachers with ChatGPT and observed that prospective teachers regarded artificial intelligence as a human-like communication tool, and the better the commands and directions given to artificial intelligence were expressed, the more desirable the responses received from artificial intelligence. In addition, it can be said that prospective teachers see artificial intelligence not only as a content producer but also as a powerful support tool when directed correctly. Apart from giving correct commands and using the correct language, the emphasis of prospective teachers on the training of artificial intelligence is noteworthy. Their emphasis on the need to train artificial intelligence can also be interpreted as being aware of issues such as ethical use and reliability. In Duran's (2024) study on the integration of artificial intelligence into education with prospective teachers, prospective teachers similarly expressed their concerns about the reliability and ethical use of artificial intelligence.

It is seen that the ideas of the prospective teachers diversified in terms of the features that the activity should have. This may be because they are aware of the fact that for the effectiveness and efficiency of mathematical activities, the implementation of the activities is as important as their design. In the context of the features that the activity should have, prospective teachers mostly emphasised the issue of appropriateness to the principles of activity design. This situation shows that prospective teachers are aware of the importance of preparing a quality activity and adopt the approach of using technology not only superficially but also by paying attention to certain pedagogical principles. Because well-designed activities according to the principles of activity design will provide active participation of students, support their cognitive processes and contribute to meaningful learning while serving certain learning outcomes and learning objectives. In addition, in the answers given, it is seen that the importance of designing the activities based on the constructivist approach that puts the student at the centre, encourages active participation and aims to develop higher order thinking skills is emphasised. Within the framework of the project titled "AI-Enhanced Teaching: Designing Innovative Lesson Plans", which was carried out within the scope of the eTwinning programme based on international partnership and carried out within the Faculty of Education of Afyon Kocatepe University in 2025, prospective teachers prepared lesson plans and teaching activities using artificial intelligence tools. Similarly, in this process, prospective teachers produced content in line with the principles of activity design, taking into account elements such as structuring for learning objectives, student-centred approach and comprehensibility.

It was concluded that prospective mathematics teachers had difficulties in revising the activities given by artificial intelligence, the effectiveness of the activity ideas given by artificial intelligence and using artificial intelligence while preparing activities with artificial intelligence. In the difficulties in revising the activities given by artificial intelligence, prospective teachers focused on the issues of concretising the activity, making it appropriate to the design principles and editing the prepared activities. It can be said that not only prospective teachers do not consider the activities prepared by artificial intelligence appropriate for the level of students but also they think that the prepared activities are abstract. They also think that reorganising the prepared activities in terms of language, structure and content is a burden for them. It was emphasised that the activity suggestions provided by artificial intelligence are generally superficial, far from creativity, and often contain content that is not suitable for the student level. Especially the fact that a large number of participants emphasised that the activities were superficial shows that they did not directly use the content produced by artificial intelligence and questioned the adequacy of the content. It can be stated that this situation arises from the fact that the prospective teachers are aware of the principles of activity design. Similarly in the 'AI-Enhanced Teaching: Designing Innovative Lesson Plans' project carried out within the Faculty of Education of Afyon Kocatepe University in 2025, prospective teachers reconstructed the outputs obtained from artificial intelligence by making critical evaluations on these outputs instead of using them directly. It can be stated that the pedagogical knowledge and sensitivity of the prospective teachers are revealed here. In this context, instead of putting artificial intelligence directly at the centre of the teaching process, prospective teachers try to give artificial intelligence a role that enriches and facilitates the teaching process. All these efforts point to the conclusion that prospective teachers use artificial intelligence as a guide. Similarly, Tapan Broutın (2024) examined the processes of prospective mathematics teachers in creating course plans using artificial intelligence and concluded that prospective teachers used artificial intelligence as a guide. This research supports the results of the study. Finally, the conclusion that there are some technical difficulties in the processes of using artificial intelligence points to the importance of digital literacy. In particular, technical difficulties such as difficulties in communicating, message limits, receiving continuous feedback may prevent prospective teachers from managing the process efficiently. Similarly, Tapan Broutın (2023) concluded in his study that teachers should provide correct commands and directions and receive training on this subject in order to obtain the information they want from artificial intelligence.

Finally, it was concluded that the process of preparing activities supported by artificial intelligence contributed to the development of prospective mathematics teachers and their knowledge about artificial intelligence. The fact that the prospective teachers stated that it contributed to their self-development at the point of having knowledge about artificial intelligence increased their awareness, especially about how artificial intelligence can be used in mathematics teaching. In addition, it provides benefits in terms of how to ask questions to artificial intelligence, how to direct it, how to communicate briefly. In the study conducted by Eager and Brunton (2023), the emphasis on the need to express what is desired from artificial intelligence in a descriptive manner and to use commands with clear boundaries supports the results of the study. Lo et al. (2023) stated that clear, concise, logically structured and adaptive commands should be used to improve the performance of artificial intelligence models to produce the desired results. Previous research on ChatGPT and prompt engineering has also shown that progressively structured inputs lead to better, more efficient and realistic results (Grabb, 2023; Spasić and Janković, 2023). However, it was concluded in the study that the process of preparing activities with artificial intelligence gave them the opportunity to get to know this technology more closely. Similarly, the study emphasizes that artificial intelligence tools play an important role in developing prospective teachers' technological pedagogical content knowledge (Mishra & Koehler, 2006).

In addition, it is of great importance to conclude that the artificial intelligence-supported activity design process contributed to the individual and professional improvement of prospective teachers.

Indeed, the inclusion of artificial intelligence in the teacher education process enables both the development of pedagogical skills and the preparation of teaching materials to become more qualified and efficient (Holmes et al., 2019; Zawacki-Richter et al., 2019).

It is important that prospective teachers stated that the process of preparing activities with artificial intelligence contributed to them in terms of gaining criticism skills, acquiring different information and different perspectives, and creating effective visuals and drafts. Because this situation directly affects the professional life of teachers and can enrich the teaching process. In parallel with this situation; Baytak (2024) conducted a content analysis of the course plans created by ChatGPT and Google Gemini in his study. In particular, ChatGPT demonstrated the ability to help create comprehensive course plans that include a variety of instructional strategies and resources, suggest activities, exercises and examples to illustrate mathematical concepts, and offer the flexibility to be customised to suit students' different learning paces and styles, thereby increasing the accessibility of mathematical concepts for all students. In the study, only one participant group stated that the process of preparing activities with artificial intelligence did not make any contribution to them. This situation points to the importance of individual differences and attitudes towards technological innovations. The diversity of prospective teachers' perceptions and experiences regarding artificial intelligence technologies shows that such applications should be designed in a more inclusive and supportive manner for different learning styles.

As a result, integrating artificial intelligence tools into teacher education programmes not only increases prospective teachers' information technology literacy but also helps them to be more creative, effective and efficient in pedagogical practices.

Suggestions

In line with the results obtained in the study, the following suggestions can be mad:

- It can be ensured that prospective teachers prepare activities in different outcomes and subjects and these activities can be analysed.

- In order to overcome the difficulties encountered by prospective teachers in the preparation of artificial intelligence-based activities, digital resources can be created to guide this process.
- Faculties of education can improve the technological literacy and pedagogical competences of prospective teachers through applied courses that include the effective use of artificial intelligence tools.
- Workshops and seminars can be organised to increase the knowledge and experience of teachers about artificial intelligence throughout their professional life and effective guidance can be provided to them about artificial intelligence.

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EXAMINING THE USE OF TECHNOLOGY IN THE 5TH GRADE MATHEMATICS TEXTBOOK PREPARED ACCORDING TO THE MAARIF MODEL

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Introduction

In order to provide 21st century skills, areas such as digital literacy, critical thinking, problem solving and technology use are becoming increasingly important in education. The Türkiye Century Education Model aims to develop students' cognitive, affective and digital skills by taking into account the needs of this age. In particular, when mathematics education is supported by technology, it increases students' active participation in learning processes, helps abstract concepts to be concretized and ensures the permanence of learning. The Türkiye Century Education Model aims to provide a student-centered and skill-focused transformation in our education system in line with the requirements of the age. The textbooks that form the basis of this model are also being restructured in line with this vision. The 5th grade mathematics textbook; especially in the basic education level, aims to develop students' mathematical thinking skills, increase their problem-solving abilities and relate mathematics to daily life. Technology-supported mathematics teaching offers strong opportunities in terms of enriching, individualizing and visualizing learning environments. In this context, educational technologies should be considered not only as tools but also as a pedagogical environment (Koehler & Mishra, 2009). The use of technology in mathematics education manifests itself in various forms such as dynamic geometry software, mobile applications, simulations, interactive boards, mathematical tools and learning management systems. When course designs are planned in accordance with teaching methods and techniques and effective use of technology is planned in the course process, its positive effects can be seen. Dynamic mathematics software, especially in teaching geometry subjects, enables students to visualize and internalize geometric shapes in their minds (Dahal, Pant, Shrestha, & Manandhar, 2022; Taş, 2016). The use of dynamic mathematics software has positive effects on the development of students' spatial abilities (Karaaslan, 2013; Köse & Kalay, 2018). It has been concluded in the literature that there is a significant relationship between students' spatial abilities and geometric habits of mind (Taş & Yavuz, 2020). In this direction, the use of technology in accordance with pedagogical principles can enable students to develop their geometric thinking skills and enable them to think analytically and make inferences in different problem situations. Students can usually use smartphones, tablets, and computers easily from a young age and are interested in these tools. In this process, by including these tools when designing the teaching environment, students' interest in mathematics and the learning process and their success can be increased. Mobile applications developed for mathematics can be included in the content of textbooks for use in face-to-face and distance education. There are various studies in the literature investigating the effects of the use of mobile applications developed for mathematics course subjects on students' face-to-face and distance education processes. As a result of the studies, it has been concluded that the use of mobile applications developed for mathematics subjects provides students with positive views towards distance education (Taş & Yavuz, 2023c). In this context, mobile applications can be included in the learning-teaching process of mathematics subjects.

The Türkiye Century Education Model defines technology not as a goal but as a tool that supports the learning-teaching process. The model's suitability for the requirements of the digital age is provided by technological applications related to interdisciplinary thinking and production skills. The Türkiye Century Education Model aims to use it effectively to enrich learning processes, increase student participation and provide learning environments suitable for individual learning speeds. The model recommends that technology should be transferred by associating it with pedagogical approaches that will contribute to students' development of critical thinking, creativity, collaboration and communication skills, beyond being a mere tool for accessing information.

In the 5th grade mathematics textbook, technology is integrated into various learning areas, aiming to help students understand mathematical concepts more concretely, appeal to different learning styles, and increase their motivation. In the integration of technology, it is important to plan and include areas that will make it easier for students to be active in the learning process and make sense of concepts. Some of these areas can be expressed as follows:

- Digital Materials Supporting Conceptual Understanding: Interactive animations, simulations, and virtual manipulatives can be included in the textbook or external resources can be directed to concretize and visualize abstract mathematical concepts. For example; dynamic models can be used to explain fractions, and 3D visualizations can be used to examine the properties of geometric shapes.
- Applications that Improve Problem Solving Skills: Simulations of problem situations based on real-life scenarios can allow students to try different solution strategies and see the results immediately. In addition, simple coding activities or applications that support algorithmic thinking can encourage students to approach mathematical problems from different perspectives.
- Activities that gamify learning: Educational games and applications that enable learning mathematical concepts in a fun way can be suggested in the textbook or links to such resources can be provided. Gamification supports students' active participation in the learning process by increasing their motivation. For example, interactive games that make the repetition of basic operations fun can be used.
- Data Analysis and Interpretation Tools: Basic graphical drawing tools or applications that can be used to visualize and interpret simple data sets can be included in the textbook. These tools help students develop their skills in reading, interpreting, and making inferences about data.
- Platforms that Support Collaboration and Communication: Online platforms or tools that will enable students to solve mathematical problems together, exchange ideas, and share their solutions can be

referenced in the textbook. This encourages peer learning and social interaction.

- Individualized Learning Opportunities: Adaptive learning platforms or applications that students can use to progress according to their own learning pace and needs can be directed in the textbook. In this way, each student is supported to understand mathematical concepts in depth.
- Assessment and Feedback Mechanisms: Online assessment tools or applications that students can use to track their own learning processes and receive instant feedback can be included in the textbook.

The use of technology in the 5th grade mathematics textbook should be carefully planned in line with pedagogical principles. Technology should not be the primary purpose of learning, but a tool that supports and enriches learning. Some points to consider in this context are as follows:

- Accessibility and Equality: Whether all students have access to technological tools and the internet should be considered, and alternative learning methods should be offered.
- Integration with Pedagogical Purpose: Technology should directly contribute to the understanding of mathematical concepts and the development of skills. It should not be used solely for the purpose of attracting attention or entertaining.
- Teacher Guidance: Necessary training and support should be provided for teachers to use technological tools effectively. Teacher guides and suggestions for technology integrations in the textbook should be provided.
- Screen Time and Health: The possible negative effects of students spending long periods in front of the screen should be considered, and the duration of technology use should be balanced.
- Security and Privacy: Student safety and the protection of personal data should be prioritized in the use of online tools.

The place and use of technology in the textbook are of great importance. In this study, the 5th grade mathematics textbook published in accordance with the Maarif Model in 2024 was examined in terms of content, and the extent to which technology use was included, how this use was integrated with learning outcomes, and how students' interaction with technological tools was encouraged was analyzed.

The research problem, which was carried out to determine how technology is positioned in the 5th grade mathematics textbook prepared within the framework of the Turkey Century Maarif Model and how it is integrated into the learning processes is; "How is the use of technological tools included in the 5th grade Mathematics textbook prepared according to the Türkiye Century Maarif Model 2024 Middle School Mathematics course curriculum?" depending on this problem;

1. What is the type and frequency of use of technological tools/content in the 5th grade Mathematics textbook prepared according to the Maarif Model?
2. In which themes are the activities related to technology use addressed in the 5th grade Mathematics textbook prepared according to the Maarif Model and how are these activities thematically distributed?
3. In the 5th grade Mathematics textbook prepared according to the Maarif Model, answers were sought to the sub-problems of how technology-related activities are structured in line with the targeted learning outcomes in mathematics teaching and which mathematical field skills are presented for development?

Method

Research model

The aim of the research was to examine the use of technology in the 5th grade Mathematics textbook prepared according to the Türkiye Century Maarif Model and the themes, content and activities in the book in terms of technology use. The case study method, one of the qualitative research methods, was used. Data were collected using the document analysis technique.

Data source and data analysis

In this study, the 1st and 2nd books of the Mathematics 5th Grade Textbook, which was accepted as an educational tool with the letter dated 17.07.2024 and numbered 110460159 of the Ministry of National Education Board of Education and Training and published in 2024, were examined for the data source and data analysis. In the analysis of the obtained data, descriptive analysis, which is used to describe the findings obtained in qualitative research and to describe and interpret the obtained findings, was used (Yıldırım and Şimşek, 2016).

Limitations

This research is limited to the Middle School and Imam Hatip Middle School 5th grade Mathematics textbook prepared according to the Mathematics curriculum, which was put into practice as of the 2024-2025 academic year within the scope of the Türkiye Century Maarif Model and will be gradually implemented in other grades.

Findings

In the first sub-problem of the research, the type and frequency of use of technological tools/contents in the 5th grade Mathematics textbook prepared according to the Maarif Model were examined and the findings obtained are presented in Table 1.

Table 1. *Type and Frequency of Use of Technological Tools/Contents in 5th Grade Mathematics Textbooks*

Category	Code	Frequency (f)	Percentage (%)
Computer Related Technological Tools	Computer	1	1,1
	Tablet	1	1,1
	Laptop	1	1,1
	Interactive board	1	1,1
	Calculator	1	1,1
	Smart phone	30	32,6
Dynamic Mathematics Software	GeoGebra	11	12
	TinkerPlots	2	2,8
Mathematical Tools	Compass	8	8,7
	Ruler	15	16,3
	Gradient (Unmeasured ruler)	13	14,1
	Miter	2	2,2
	Protractor	6	6,5
TOTAL		**92**	**100**

The technological tools and contents in the 5th grade Mathematics textbooks prepared according to the Türkiye Century Maarif Model are divided into the categories of Computer-Related Technological Tools, Dynamic Mathematics Software, and Mathematical Tools according to their areas of use and functions. The reason for dividing into these categories is that each technological tool and content offers different functions and areas of use in education and provides students with various learning experiences.

When Table 1 is examined, the most frequently encountered Computer-Related Technological Tool in the 5th grade Mathematics textbooks is the smartphone. It was found that computers, tablets, laptops, interactive boards, and calculators were used equally.

The most frequently used code among dynamic mathematics software was GeoGebra, while the least frequently used was TinkerPlots. These tools were included according to theme and learning outcome.

In the mathematical tools category, ruler was used most frequently, and set square was used least frequently.

In the second sub-problem of the research, it was examined within which themes the activities related to the use of technology in the 5th grade Mathematics textbook prepared according to the Maarif Model were addressed, and the findings obtained are presented in Table 2.

Table 2. *Distribution of Technology-Related Activities in the 5th Grade Mathematics Textbook According to Thematic Framework*

	Theme	Frequency (f)	Percentage (%)
Activities using technological and mathematical tools	Theme 1: Geometric Shapes	26	83,9
	Theme 2: Numbers and Quantities (1)	1	3,2
	Theme 3: Geometric Quantities	2	6,5
	Theme 4: Numbers and Quantities (2)	1	3,2
	Theme 5: The Statistical Research Process	1	3,2
	Theme 6: Algebraic Thinking with Operations	0	0
	Theme 7: From Data to Probability	0	0
TOTAL		**31**	**100**

When Table 2 is examined, it is found that the activities where technology and mathematical tools are used most frequently in 5th grade Mathematics textbooks are in the theme of Geometric Shapes.

In the third sub-problem of the research, technology-related activities in the 5th grade Mathematics textbook prepared according to the Maarif Model, how they are structured in line with the targeted learning outcomes in mathematics teaching and which mathematical field skills they are aimed at developing were examined and the findings obtained are presented in Table 3.

Table 3. *Distribution of Activities Related to the Use of Technology in the 5th Grade Mathematics Textbook in Line with the Learning Outcomes*

	Theme	Learning Outcomes	Frequency (f)	Percentage (%)
Activities using technological and mathematical tools	Theme 1: Geometric Shapes	MAT.5.3.1. Ability to use mathematical tools and technology for basic geometric drawings	10	27,8
		MAT.5.3.2. Reflect on experiences based on basic geometric drawings	3	8,3
		MAT.5.3.3. Use mathematical tools and technology to measure angles	5	13,9
		MAT.5.3.4. Make inferences about angles that can be formed depending on the relative	5	13,9

		positions of two or three lines in the plane		
		MAT.5.3.5. Interpret polygons as closed shapes formed by consecutively intersecting lines in the plane	3	8,3
		MAT.5.3.6. Reflect on experiences gained regarding the properties of polygons	2	5,6
		MAT.5.3.7. Make judgments about the side properties of triangles constructed with the centers of a pair of circles intersecting at two points in the plane and one of their intersection points with the help of	3	8,3

		mathematical tools and technology		
	Theme 2: Numbers and Quantities (1)	MAT.5.1.1. Generalize reading and writing six-digit numbers to multi-digit numbers	1	2,8
	Theme 3: Geometric Quantities	MAT.5.4.1. Interpret side lengths when the perimeter of a rectangle with natural number side lengths is given	2	5,6
	Theme 4: Numbers and Quantities (2)	MAT.5.1.3. Represent fractions in different formats that correspond to real-life situations	1	2,8
	Theme 5: The Statistical Research Process	MAT.5.5.2. Discuss statistical results or interpretations based on categorical data created by others.	1	2,8

	Theme 6: Algebraic Thinking with Operations	-	0	0
	Theme 7: From Data to Probability	-	0	0
TOTAL			**36**	**100**

When Table 3 is examined, it is found that the use of technological and mathematical tools is included in 11 different learning outcomes according to the themes. It is found that the use of technological and mathematical tools is provided the most in the learning outcome "MAT.5.3.1. Being able to use mathematical tools and technology for basic geometric drawings".

Table 4. *Distribution of Activities Related to the Use of Technology for the Development of Mathematical Field Skills According to the Themes*

	Theme	**MFS**	**Frequency (f)**	**Percentage (%)**
Activities using technological and mathematical tools	Theme 1: Geometric Shapes	MFS1. Mathematical Reasoning MAB5. Working with Mathematical Tools and Technology	26	83,9
	Theme 2: Numbers and Quantities (1)	MFS3. Mathematical Representation MFS5. Working with Mathematical Tools and Technology	1	3,2

	Theme 3: Geometric Quantities	MFS2. Mathematical Problem Solving	2	6,5
	Theme 4: Numbers and Quantities (2))	MFS3. Mathematical Representation	1	3,2
	Theme 5: The Statistical Research Process	MFS4. Working with Data and Data-Based Decision Making	1	3,2
	Theme 6: Algebraic Thinking with Operations	-	0	0
	Theme 7: From Data to Probability	-	0	0
TOTAL			**31**	**100**

When the activities related to the use of technology in the textbook are examined according to the themes of mathematical field skills in Table 4, it is found that the most frequent use of the field skills is "MAB1. Mathematical Reasoning, MAB5. Working with Mathematical Tools and Technology".

Table 5. *Distribution of Activities Related to the Use of Technology According to Mathematical Field Skills*

	MFS	Frequency (f)	Percentage (%)
Activities using technological and mathematical tools	MFS1. Mathematical Reasoning	26	44,8
	MFS2. Mathematical Problem Solving	2	3,4
	MFS3. Mathematical Representation	2	3,4
	MFS4. Working with Data and Data-Based Decision Making	1	1,7
	MFS5. Working with Mathematical Tools and Technology	27	46,6
TOTAL		**58**	**100**

When the activities where technological and mathematical tools were used were examined, it was found that the content aimed at developing the field skill MAB5. Working with Mathematical Tools and Technology" was included the most in these activities.

Conclusion, Discussion and Recommendations

The 5th grade mathematics textbook, prepared in line with the vision of the Türkiye Century Maarif Model, considers technology as an integral part of the learning processes (MEB, 2024b, 2024c). It is aimed to make mathematics learning more effective, interesting and student-centered through digital materials, problem-solving applications, gamification, data analysis tools and platforms that support collaboration. However, it is of great importance to use technology consciously and for pedagogical purposes, to consider factors such as accessibility, teacher guidance and student health. In this way, technology will make significant contributions to students' mathematical thinking skills, increase their problem-solving abilities and gain positive attitudes towards mathematics in the 5th grade mathematics textbook. In the literature, there are research results indicating that using mathematical tools and technology has an effect on increasing students' interest, motivation and success in mathematics (Albaladejo, García, Codina, 2015; Baltacı et al., 2015; Ceylan, 2012; Karaibryamov, Tsareva, Zlatanov, 2012; Taş and Yavuz, 2022). By using technological tools, students can make sense of the properties of geometric shapes, their spatial thinking becomes easier and they can visualize the shapes more easily. In this direction, the use of technological tools is important in assimilating the concepts for each subject.

In the textbook prepared according to the Maarif Model, activities that include the use of technological tools are classified according to the categories of Computer-Related Technological Tools, Dynamic Mathematics Software, and Mathematical Tools. In the activities, students are given the opportunity to access the content at school and outside of school with smartphones and to progress according to their individual learning speeds. With the Covid-19 pandemic process, it was necessary to switch to distance education for a certain period of time. During this process, various mobile applications have started to be used more frequently in the learning process. It is concluded that teaching through mobile applications enables students to develop their interest, motivation, and attitudes towards lessons (Taş & Yavuz, 2023a). In a study, an interview was conducted with the students after the GeoHepta mobile application developed for 7th grade students was used in the learning process during the distance education period. It was determined that the students interviewed were eager and curious about the use of the mobile application and that positive thoughts about mathematics developed. It was concluded that the mobile application was fun, attractively prepared, and the activities in the content of the mobile application ensured that the subjects were better understood (Taş & Yavuz, 2023b). It is thought that the use of smartphones through the activities in the textbook will make it easier for students to learn mathematics in classroom and out-of-class environments.

It has been found that the activities for the use of technological tools in the 5th grade textbook prepared according to the Maarif Model are mostly found in the theme of Geometric Shapes. Studies in the literature indicate that using mathematical tools and technologies in concretizing and making sense of geometric shapes have positive effects on student success, interest in the lesson, motivation and motivation (Clements & Sarama, 2007; Sinclair & Bruce, 2015; Sinclair & Yerushalmy, 2016). In this context, it can be said that the addition of content for the use of technology in the activities in the theme of Geometric Shapes is one of the strengths of the program. There are 5 field skills in the mathematics curriculum. These skills are stated as Mathematical Reasoning, Mathematical Problem Solving, Mathematical Representation, Working with Data and Data-Based Decision Making, Working with Mathematical Tools and Technology (MEB, 2024a). It has been found that the activities for the use of technology in the examined textbooks most frequently aim to develop the field skill of Working with Mathematical Tools and Technology. It is expected that the field skill of Working with Mathematical Tools and Technology in the mathematics curriculum prepared according to the Maarif Model will make the use of technological tools more effective in the course process through activities.

The 5th Grade Mathematics Textbook shows that the use of technology is integrated into various learning areas. However, it is recommended that this integration be further increased and deepened. In particular, it would be useful to pay attention to the following points:

• Interactive Content: Adding more interactive content to the textbook that will enable students to actively participate can make the learning process more effective.

• Teacher Guides: Providing detailed explanations and sample applications regarding technology integration in guides prepared for teachers can increase the quality of the teaching process.

• Continuous Updates: In today's world where technology is rapidly developing, regularly updating the content of textbooks will ensure that students are equipped with up-to-date knowledge and skills.

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ALGORITHMS TO DISCUSS THE ROTATIONS BY QUATERNIONS: A MATHEMATICAL AND EDUCATIONAL PERSPECTIVE

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Introduction

This study highlights the pedagogical value of quaternions in concretizing abstract concepts encountered in transformation geometry, particularly spatial rotations. By integrating quaternion-based rotation algorithms into the learning process, teacher candidates are given the opportunity to engage with spatial transformations both algebraically and visually. This dual representation not only enhances their conceptual understanding of rotation but also supports the development of spatial reasoning skills an essential component of mathematical proficiency.

Furthermore, the use of quaternionic methods aligns well with contemporary mathematics education approaches that emphasize the integration of digital technologies and artificial intelligence into instructional practices. Quaternion-based modeling and algorithmic thinking can be incorporated into dynamic geometry software, computer programming activities, or AI-supported learning environments, thus enriching the teaching and learning experience. In this regard, the study offers an innovative educational framework that can support teacher educators in designing materials that bridge advanced mathematical theory with accessible, technology-enhanced classroom applications.

The implementation of quaternion-based geometric transformations in mathematics education offers a unique opportunity to cultivate a range of higher-order cognitive and procedural skills among learners. First and foremost, students develop a deep understanding of spatial rotations through both algebraic formulations and geometric visualizations, bridging abstract mathematical theory with tangible conceptual models. By engaging in interactive coding and modeling tasks such as constructing Python scripts or utilizing dynamic geometry software learners actively strengthen their spatial visualization abilities, which are critical for mastering three-dimensional concepts. Additionally, the process of converting between quaternion expressions and rotation matrices fosters algorithmic thinking and encourages students to establish meaningful connections between symbolic manipulation and geometric reasoning. These competencies not only enrich students' mathematical thinking but also prepare them for real-world applications by familiarizing them with computational tools frequently used in interdisciplinary domains such as robotics, computer graphics, and aerospace engineering. As a result, the educational use of quaternions not only enhances geometry instruction but also aligns with the broader goals of STEM education by promoting integration across mathematical and technological literacies.

The study of rotations in three-dimensional Euclidean space is a foundational topic in geometry, physics, and computer science. In this work, we explore the geometric characteristics of rotations through the algebraic formalism provided by unit quaternions. The main objective is to formulate and analyze rotation transformations using quaternionic representations, offering a unified, compact, and elegant approach rooted in geometric algebra (Gracia & Thomas, 2017; Özdemir, 2016).

Initially, two linear transformations are rigorously introduced to model rotations: one about the origin and another around an arbitrary point in Euclidean space. These transformations are expressed in terms of quaternion multiplication, and their effects on arbitrary vectors are analyzed in detail. Matrix representations of these transformations are derived to enable spectral analysis, where eigenvalues and eigenvectors are computed and interpreted geometrically. This analysis provides insights into invariant directions and the influence of quaternion components on the nature of the corresponding rotations (Erdoğdu & Özdemir, 2015). The identity transformation, which maps every point to itself, is trivially a rigid motion. Furthermore, the composition of two rigid motions results in another rigid motion, indicating closure under composition. In addition, every rigid motion possesses an inverse that is itself a rigid motion. As a result, the collection of all rigid motions of a given Euclidean space satisfies the group axioms (closure, associativity, identity, and invertibility), thereby forming a group under the operation of composition. This group is referred to as the Euclidean group, typically denoted as $\mathbb{E}^n$ for n-dimensional Euclidean space. Each element of the Euclidean group can be uniquely decomposed into the composition of a translation and an orthogonal linear transformation. Specifically, if a rigid motion acts on a vector $\vec{u}$ in $\mathbb{E}^n$, it can be represented in the form

$$T(\vec{u}) = A\vec{u} + \vec{b},$$

where A is an orthogonal matrix (representing the linear transformation part) and $\vec{b}$ is a constant vector in $\mathbb{E}^n$ (representing translation). Thus, understanding the linear part of a rigid motion requires an in-depth examination of orthogonal transformations. A linear transformation

$$T: \mathbb{E}^n \to \mathbb{E}^n$$

is said to be orthogonal if it preserves the norm (or length) of every vector in the space, that is,

$$\|T(\vec{u})\| = \|\vec{u}\|$$

for all vector $\vec{u}$ in $\mathbb{E}^n$. Since the Euclidean norm defines the metric of the space, this property ensures that distances between all pairs of vectors are preserved. Hence, orthogonal transformations are isometries that fix the origin, and they form the backbone of the study of rigid motions. The matrix representation of an orthogonal transformation is an orthogonal matrix, which is a $n \times n$ matrix T satisfying the condition

$$T^t T = T T^t = I_n$$

where T^t denotes the transpose of T, and I_n is the $n \times n$ identity matrix. This condition implies that the inverse of an orthogonal matrix is equal to its transpose, i.e., $T^{-1} = T^t$. This elegant algebraic property ensures numerical stability and geometric invariance, making orthogonal matrices indispensable in applications such as computer graphics, rigid body dynamics, and differential geometry.

Moreover, the set of all $n \times n$ orthogonal matrices with real entries forms a group under matrix multiplication, known as the orthogonal group, denoted by $O(n)$. This group not only satisfies the group axioms but also possesses a rich geometric and topological structure. In conclusion, the group of rigid motions in Euclidean space comprising translations and orthogonal transformations forms a foundational structure in geometry and physics. The orthogonal group $O(n)$, as a compact Lie group, provides the mathematical apparatus necessary to understand the rotational and reflectional symmetries inherent in physical space, and its associated Lie algebra offers further insight into the infinitesimal structure of these symmetries. Introducing orthogonal transformations to students through the use of quaternions can significantly enhance both their conceptual understanding and their ability to apply mathematical tools to real-world problems in geometry and physics. Quaternions, as an extension of complex numbers, offer a compact and elegant algebraic structure that simplifies the representation of rotations in three-dimensional space and, with appropriate extensions, in four-dimensional space as well. Unlike traditional matrix-based methods, which often require the use of 3×3 or 4×4 orthogonal matrices and can be computationally intensive or geometrically opaque, quaternions reduce the complexity of these operations while preserving full geometric meaning. This simplification helps students to better visualize and internalize how rotations work, particularly the idea of rotating around an arbitrary axis in space (Friedberg et al., 2003; Roman, 2008).

The set of all such orthogonal matrices forms a group under matrix multiplication, known as the orthogonal group O(n), which exhibits rich geometric and algebraic structures. Within this group, special orthogonal transformations that preserve orientation form the subgroup SO(n). These concepts are essential in modeling symmetry and motion in rigid body dynamics and theoretical frameworks such as Lie groups and differential geometry (Gürlebeck & Sprössig, 1997). Quaternions offer a powerful alternative to traditional matrix-based rotation representations. Unlike Euler angles or rotation matrices, unit quaternions avoid singularities (such as gimbal lock) and allow more efficient and stable interpolation of orientations. Their algebraic properties make them particularly suitable for applications in computer graphics, aerospace navigation, and biomechanics (Ablamowicz & Sobczyk, 2003; Özdemir & Ergin, 2006). Moreover, quaternions facilitate an intuitive understanding of rotation as a transformation about an arbitrary axis in space. The unit quaternions form a Lie group isomorphic to SO(3), providing a natural bridge between linear algebra, geometric algebra, and group theory. This connection enriches the pedagogical value of quaternions, making them an effective tool for introducing advanced mathematical structures in an accessible way.

Quaternions and rotations

In mathematics education, particularly in the teaching of spatial geometry and transformation topics, students often struggle to visualize and comprehend abstract concepts such as rotations in three-dimensional space. Traditional instructional approaches relying solely on matrices or coordinate transformations may fall short in promoting deep conceptual understanding. In this context, quaternions offer a powerful and intuitive tool to help students grasp the nature of spatial rotations more effectively. Their compact algebraic structure and geometric clarity provide a meaningful bridge between abstract mathematical theory and concrete spatial reasoning.

By enabling learners to represent and manipulate rotations in an elegant and efficient way, quaternions contribute to the development of both procedural fluency and conceptual insight. Therefore, this study not only addresses the mathematical foundations of rotations using quaternions but also serves as a pedagogical resource for pre-service mathematics teachers and educators seeking to implement innovative instructional approaches in geometry education. Through the integration of quaternion-based algorithms and visual representations, this work supports the design of learning environments that foster mathematical thinking, spatial visualization, and interdisciplinary connections aligned with STEM education goals.

Quaternions, a mathematical extension of complex numbers to four dimensions, were discovered by Sir William Rowan Hamilton in 1843. This groundbreaking discovery laid the foundation for a new algebraic framework, which was later expanded and formalized in the early 20th century to include practical applications, particularly in the geometric interpretation of spatial rotations. Among the most significant features of quaternions is that every unit quaternion corresponds to a rotation in three-dimensional Euclidean space, a property that has rendered them especially valuable in the study of rigid body dynamics, computer graphics, and physics.

In Euclidean 3-space, various methods exist to represent rotations, such as orthonormal matrices, Euler angles, and unit quaternions. Among these, unit quaternions offer a more compact, numerically stable, and geometrically intuitive alternative. Unlike Euler angles, they avoid singularities like gimbal lock, and unlike rotation matrices, they require fewer parameters and are computationally more efficient when interpolating or composing rotations. As such, quaternions are widely regarded as a more natural and elegant way to understand and manipulate rotations in three-dimensional space. A comprehensive comparison of these rotational representation methods, including a discussion on their computational efficiency and geometric fidelity, can be found in references (Gracia and Thomas; 2017) and (Özdemir; 2016). Although the theoretical importance of quaternions was recognized in the 19th century, their practical use remained limited until the mid-20th century. This situation changed dramatically with the rapid advancement of digital technologies in areas such as robotics, aerospace navigation, animation, and real-time computer graphics. These fields demand efficient and robust algorithms for handling 3D transformations, which has led to a resurgence of interest in quaternion-based methods. Today, quaternions are indispensable in applications involving computer vision, keyframe animation, virtual and augmented reality, drone and spacecraft attitude control, and optimization problems related to rigid body motion estimation (Özdemir; 2016).

Beyond Euclidean applications, quaternions and their extensions, such as split quaternions and hyperbolic quaternions have also found significant roles in the study of rotations in Lorentzian geometry and Minkowski space, which are essential in the context of special relativity. In (Özdemir and Ergin; 2006), rotations about non-null axes in Minkowski 3-space are investigated using unit split quaternions, an algebraic structure adapted to the indefinite metric of Lorentzian spaces. The eigenvalues and eigenvectors of associated Lorentzian rotation matrices are then expressed in terms of components of the corresponding split quaternions in (Özdemir et al; 2014), allowing for a classification of Lorentzian rotations as either Euclidean-like or hyperbolic, based on the scalar part of the quaternion. In (Nesovic;

2016), a new approach is developed for characterizing null-axis Lorentzian rotations through the application of Rodrigues' rotation formula and Cayley transforms, employing a pseudo-orthonormal frame constructed from two linearly independent normalized null vectors and one unit spacelike vector. The study further proves that every unit timelike split quaternion with a null vector part corresponds to a Lorentzian rotation about a null axis. Moreover, in (Ünal et al; 2016), rotations constrained to lie on a given null-cone are explored using a combination of Rodrigues' and Cayley formulas along with hyperbolic quaternions, extending the classical results into the realm of indefinite geometry. Complementarily, the study in (Şimşek and Özdemir; 2017) extends this analysis to explore rotations constrained to lie on a hyperboloid, another fundamental geometric surface in Lorentzian settings. Elliptic-type rotations are also addressed in (Gracia and Thomas; 2017), where a diverse range of mathematical tools including Rodrigues' rotation formula, the Cayley transform, even numbers of Householder transformations, and elliptic quaternions are synthesized to construct generalized elliptic rotations. Additionally, references (Şimşek and Özdemir; 2016) and (Erdoğdu and Özdemir; 2015) investigate various types of Lorentzian rotations directly within Minkowski space-time, laying a foundation for applying quaternionic and matrix-based methods to relativity and theoretical physics. In a different line of development, Lorentzian transformations are examined through Lorentzian matrix multiplications in (Özdemir; 2016) and (Keçelioğlu et al. 2012), offering matrix-based formulations that complement the quaternionic approach. Furthermore, in (Gonzalez et al. 2009), the homothetic Cayley transform and homothetic motion are introduced, along with modified Rodrigues and Euler parameters tailored to such transformations. These extensions provide a flexible algebraic framework for describing scaled rotations in geometries where the metric is not preserved.

In summary, quaternions and their variants provide a robust and unified framework for understanding and performing rotations not only in classical Euclidean settings but also in relativistic and non-Euclidean geometries. Their theoretical elegance, coupled with computational advantages and practical versatility, has established quaternions as a central tool in both modern mathematics and applied sciences.

Quaternion algebra and its properties

Beyond its theoretical significance, the study of quaternion algebra can offer valuable contributions to mathematics education, particularly in fostering students' understanding of abstract algebraic structures. Introducing quaternions in advanced high school or undergraduate curricula provides a meaningful context for exploring non-commutative operations, the concept of division algebras, and the extension of complex numbers. These topics, often perceived as purely formal, gain intuitive clarity when learners observe how quaternion multiplication directly relates to geometric transformations such as rotations in space. Additionally, the decomposition of a quaternion into scalar and vector parts presents a concrete example of mathematical abstraction that can support students' transition from procedural arithmetic to structural algebra. By connecting these algebraic properties to visual and spatial reasoning tasks such as rotating vectors or constructing 3D simulations educators can promote deeper conceptual understanding and highlight the applicability of algebra beyond symbolic manipulation. Consequently, quaternion algebra serves as a powerful instructional tool to bridge algebraic reasoning with geometric and computational thinking in mathematics education.

Quaternion algebra $\mathbb{H}$ is an associative, non-commutative division ring with four basic elements $\{\mathbf{1}, \boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}\}$ with the product rules:

$*$	$\mathbf{1}$	$\boldsymbol{i}$	$\boldsymbol{j}$	$\boldsymbol{k}$
$\mathbf{1}$	$\mathbf{1}$	$\boldsymbol{i}$	$\boldsymbol{j}$	$\boldsymbol{k}$
$\boldsymbol{i}$	$\boldsymbol{i}$	$-\mathbf{1}$	$\boldsymbol{k}$	$-\boldsymbol{j}$
$\boldsymbol{j}$	$\boldsymbol{j}$	$-\boldsymbol{k}$	$-\mathbf{1}$	$\boldsymbol{i}$
$\boldsymbol{k}$	$\boldsymbol{k}$	$\boldsymbol{j}$	$-\boldsymbol{i}$	$-\mathbf{1}$

Quaternions are a generalization of complex numbers. Also, the quaternion algebra is the even subalgebra of the Clifford algebra of the 3-dimensional Euclidean space (Özkaldı and Gündoğan;2010). We write any quaternion in the form $\boldsymbol{q} = (\boldsymbol{q_0}, \boldsymbol{q_1}, \boldsymbol{q_2}, \boldsymbol{q_3}) = \boldsymbol{q_0} + \boldsymbol{q_1 i} + \boldsymbol{q_2 j} + \boldsymbol{q_3 k}$ or

$$\boldsymbol{q} = \boldsymbol{S}(\boldsymbol{q}) + \boldsymbol{V}(\boldsymbol{q})$$

where the symbols

$$\boldsymbol{S}(\boldsymbol{q}) = \boldsymbol{q_0}$$

and

$$\boldsymbol{V}(\boldsymbol{q}) = \boldsymbol{q_1 i} + \boldsymbol{q_2 j} + \boldsymbol{q_3 k}$$

denote the scalar and vector parts of $\boldsymbol{q}$. If $\boldsymbol{S}(\boldsymbol{q}) = \boldsymbol{0}$ then $\boldsymbol{q}$ is called pure quaternion. The set of pure quaternions is denoted by $\mathbb{H}_{\boldsymbol{0}}$. The quaternion product

$$\boldsymbol{q} * \boldsymbol{p} = (\boldsymbol{q_0} + \boldsymbol{q_1 i} + \boldsymbol{q_2 j} + \boldsymbol{q_3 k}) * (\boldsymbol{p_0} + \boldsymbol{p_1 i} + \boldsymbol{p_2 j} + \boldsymbol{p_3 k})$$

is obtained by distributing the terms on the right as in ordinary algebra, except that the order of the units must be preserved and then replacing each product of units by the quantity given above table. The conjugate of the quaternion $\boldsymbol{q}$ is denoted by $\overline{\boldsymbol{q}}$, and defined as

$$\overline{\boldsymbol{q}} = \boldsymbol{S}(\boldsymbol{q}) - \boldsymbol{V}(\boldsymbol{q}).$$

The norm of a quaternion $\boldsymbol{q} = (\boldsymbol{q_1}, \boldsymbol{q_2}, \boldsymbol{q_3}, \boldsymbol{q_4})$ is defined by

$$\sqrt{\boldsymbol{q} * \overline{\boldsymbol{q}}} = \sqrt{\overline{\boldsymbol{q}} * \boldsymbol{q}} = \sqrt{\boldsymbol{q_0^2} + \boldsymbol{q_1^2} + \boldsymbol{q_2^2} + \boldsymbol{q_3^2}}$$

and is denoted by $\|\boldsymbol{q}\|$ and we say that $\boldsymbol{q}/\|\boldsymbol{q}\|$ is unit quaternion where $\boldsymbol{q} \neq \boldsymbol{0}$ [5,6,11]. With the aid of the quaternion algebra, rotations in Euclidean space may be dealt with in a simple and elegant manner. If $\boldsymbol{q}$ and $\boldsymbol{r}$ are any non-scalar quaternions, then

$$\boldsymbol{r'} = \boldsymbol{q} * \boldsymbol{r} * \boldsymbol{q}^{-\boldsymbol{1}}$$

is a quaternion whose norm and scalar part are the same as for $\boldsymbol{r}$. The vector $\boldsymbol{V}(\boldsymbol{r'})$ is obtained by revolving $\boldsymbol{V}(\boldsymbol{r})$ conically about $\boldsymbol{V}(\boldsymbol{q})$ through twice the angle of $\boldsymbol{q}$ (Vilkins; 1844).

The set of unit quaternions is denoted by

$$\mathbb{H}_{\boldsymbol{1}} = \{\boldsymbol{q} = (\boldsymbol{q_0}, \boldsymbol{q_1}, \boldsymbol{q_2}, \boldsymbol{q_3}) : \boldsymbol{q_0}, \boldsymbol{q_1}, \boldsymbol{q_2}, \boldsymbol{q_3} \in \mathbb{R}, \boldsymbol{q_0^2} + \boldsymbol{q_1^2} + \boldsymbol{q_2^2} + \boldsymbol{q_3^2} = \boldsymbol{1}\}.$$

Every unit quaternion can be written in the form

$$\boldsymbol{q_0} = \mathbf{cos}\boldsymbol{\theta} + \boldsymbol{u}\mathbf{sin}\boldsymbol{\theta}$$

where $\boldsymbol{u}$ is a unit vector satisfying the equality $\boldsymbol{u} * \boldsymbol{u} = \boldsymbol{-1}$ and is called the axis of the quaternion. The most important property of quaternions is that every unit quaternions represents a rotation in $\mathbb{E}^{3}$. That is any four numbers are enough to represent a rotation but there is only one constraint which is that the norm of the quaternion must be 1 (Özdemir and Ergin; 2006).

Every unit quaternion

$$\boldsymbol{q} = \boldsymbol{q_0} + \boldsymbol{q_1 i} + \boldsymbol{q_2 j} + \boldsymbol{q_3 k} = \boldsymbol{cos\theta} + \boldsymbol{u\, sin\theta} = \boldsymbol{cos\theta} + (\boldsymbol{u_1 i} + \boldsymbol{u_2 j} + \boldsymbol{u_3 k})\, \boldsymbol{sin\theta}$$

represents a rotation about the rotation axis u by angle 2θ by the linear transformation:

$$\boldsymbol{R_q}: \mathbb{R}^3 \rightarrow \mathbb{R}^3$$

which is defined as:

$$\boldsymbol{R_q}(\boldsymbol{x}) = \boldsymbol{q\, x\, q^{-1}} = \boldsymbol{q\, x\, \bar{q}}$$

Here, $\boldsymbol{x} = \boldsymbol{x_1 i} + \boldsymbol{x_2 j} + \boldsymbol{x_3 k} \in \mathbb{R}^3$ is a pure quaternion. Using a unit quaternion q, one can generate a rotation matrix as follows:

$$\boldsymbol{R} = [\boldsymbol{R_{sl}}] = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & -2q_0q_3 + 2q_1q_2 & 2q_0q_2 + 2q_1q_3 \\ 2q_1q_2 + 2q_0q_3 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 - 2q_0q_1 \\ 2q_1q_3 - 2q_0q_2 & 2q_0q_1 + 2q_2q_3 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$

On the other hand, we can find a unit quaternion corresponding to a given rotation matrix in $\mathbb{R}^3$ using the following formulas:

$$q_0^2 = \frac{1}{4}(R_{11} + R_{22} + R_{33}),$$

$$q_1 = \frac{1}{4q_0}(R_{32} - R_{23}),$$

$$q_2 = \frac{1}{4q_0}(R_{13} - R_{31}),$$

$$q_3 = \frac{1}{4q_0}(R_{21} - R_{12})$$

for $\boldsymbol{q_0} \neq 0$. When $\boldsymbol{q_0} = 0$, we can find the corresponding unit quaternion using:

$$\boldsymbol{q}_2 = \frac{\boldsymbol{R}_{12}}{2\boldsymbol{q}_1},$$
$$\boldsymbol{q}_3 = \frac{\boldsymbol{R}_{13}}{2\boldsymbol{q}_1},$$
$$\boldsymbol{q}_1^2 = \boldsymbol{1} - \boldsymbol{q}_2^2 - \boldsymbol{q}_3^2.$$

The function $\boldsymbol{f}: \boldsymbol{S}_3 \cong \boldsymbol{H}_1 \to \boldsymbol{SO}(\boldsymbol{3})$, which sends $\boldsymbol{q} = (\boldsymbol{q}_0, \boldsymbol{q}_1, \boldsymbol{q}_2, \boldsymbol{q}_3)$ to matrix $\boldsymbol{R}$, is a homomorphism of groups. The kernel of $\boldsymbol{f}$ is $\{\pm\boldsymbol{1}\}$, so the rotation matrix corresponds to the pair ±q of the unit quaternion. In particular, SO(3) is isomorphic to the quotient group $\boldsymbol{H}_1 \,/\, \{\pm\boldsymbol{1}\}$ by the first isomorphism theorem. In other words, for every rotation in $\mathbb{R}^3$, there are two unit quaternions that determine this rotation: $\boldsymbol{q}$ and $-\boldsymbol{q}$. So, for every rotation matrix, we can find only one unit quaternion whose first component is positive.

Quaternion and rotation matrix conversion algorithms

From an educational standpoint, incorporating quaternion-to-matrix conversion algorithms into mathematics instruction presents a valuable opportunity to integrate coding, visualization, and abstract mathematical reasoning. These algorithmic processes allow students to see how symbolic algebraic expressions (quaternions) correspond to concrete geometric actions (rotations), thereby reinforcing the connection between algebra and geometry. By implementing these algorithms using programming languages such as Python, learners engage in computational thinking while deepening their understanding of rotational transformations in three-dimensional space. Such activities align well with modern mathematics curricula that emphasize mathematical modeling, interdisciplinary applications, and digital literacy. Moreover, coding-based tasks enhance student motivation and provide a dynamic learning environment where abstract mathematical concepts are brought to life through simulation and visualization.

We will explain two Python algorithms that demonstrate the conversion between unit quaternions and 3×3 rotation matrices. These conversions are essential in fields such as robotics, aerospace, and computer graphics for describing and performing 3D rotations with numerical stability and geometric clarity. Each unit quaternion represents a unique rotation in 3D space and can be transformed into a rotation matrix and vice versa. Below are the detailed explanations and implementations of both algorithms.

Quaternion to Rotation Matrix Case: Given a unit quaternion $q = (q0, q1, q2, q3)$, where $q0$ is the scalar part and $(q1, q2, q3)$ is the vector part, the following algorithm calculates the corresponding 3×3 rotation matrix. This matrix performs the same rotation as the quaternion in 3D Euclidean space. This transformation is particularly useful because quaternions offer a more compact and stable representation than Euler angles or rotation matrices alone.

Algorithm:

import numpy as np

def quaternion_to_rotation_matrix(q):

Converts a unit quaternion into its corresponding 3×3 *rotation matrix.*
Parameters:
q : tuple or list

The quaternion components (q0, q1, q2, q3), where q0 is the scalar part and (q1, q2, q3) form the vector part. The quaternion must be a unit quaternion.

Returns:

R : np.ndarray

The 3×3 *rotation matrix corresponding to the given quaternion.*

q0, q1, q2, q3 = q

R = np.array ([[q0**2 + q1**2 - q2**2 - q3**2, -2*q0*q3 + 2*q1*q2,

2*q0*q2 + 2*q1*q3],

[2*q1*q2 + 2*q0*q3, q0**2 - q1**2 + q2**2 - q3**2, 2*q2*q3 – 2*q0*q1], [2*q1*q3 - 2*q0*q2, 2*q0*q1 + 2*q2*q3, q0**2 - q1**2 – q2**2 + q3**2]]) return R

Rotation Matrix to Quaternion Case: Given a 3×3 rotation matrix R, this algorithm computes the equivalent unit quaternion $(q0, q1, q2, q3)$. The conversion is based on the matrix trace and diagonal elements to maintain numerical stability. This reverse conversion is valuable when working with data from motion capture systems or physics engines, where rotation matrices are often used but quaternions are preferred for interpolation and composition.

Algorithm:
def rotation_matrix_to_quaternion(R):

Converts a 3x3 rotation matrix into the corresponding unit quaternion (q0, q1, q2, q3).

Parameters:
R : np.ndarray

A *3x3* rotation matrix (orthogonal with determinant +1)

Returns:

q : tuple

The unit quaternion (q0, q1, q2, q3), where q0 is the scalar part.
trace = np.trace(R)

if trace > 0:

q0 = np.sqrt(1.0 + trace) / 2.0

q1 = (R[2,1] - R[1,2]) / (4.0 * q0)

q2 = (R[0,2] - R[2,0]) / (4.0 * q0)

q3 = (R[1,0] - R[0,1]) / (4.0 * q0)

else:

if R[0,0] > R[1,1] and R[0,0] > R[2,2]:

q1 = np.sqrt(1.0 + R[0,0] - R[1,1] - R[2,2]) / 2.0

q0 = (R[2,1] - R[1,2]) / (4.0 * q1)

```
q2 = (R[0,1] + R[1,0]) / (4.0 * q1)
q3 = (R[0,2] + R[2,0]) / (4.0 * q1)
elif R[1,1] > R[2,2]:
q2 = np.sqrt(1.0 + R[1,1] - R[0,0] - R[2,2]) / 2.0
q0 = (R[0,2] - R[2,0]) / (4.0 * q2)
q1 = (R[0,1] + R[1,0]) / (4.0 * q2)
q3 = (R[1,2] + R[2,1]) / (4.0 * q2)
else:
q3 = np.sqrt(1.0 + R[2,2] - R[0,0] - R[1,1]) / 2.0
q0 = (R[1,0] - R[0,1]) / (4.0 * q3)
q1 = (R[0,2] + R[2,0]) / (4.0 * q3)
q2 = (R[1,2] + R[2,1]) / (4.0 * q3)
return (q0, q1, q2, q3)
```

An application of conversion algorithms

Consider the following unit quaternion is given:

$q = (\cos(45^{\circ}), \sin(45^{\circ}), 0,0) = (0.7071,0.7071,0,0)$

This quaternion represents a rotation with:

Rotation angle: 2θ=$2 \times 45^{\circ}$= 90°, since unit quaternions encode half the rotation angle.

Rotation axis: $u = (1,0,0)$ which is the x-axis.

Interpretation: This quaternion performs a counterclockwise 90° rotation around the x −axis.

Rotation matrix obtained from the quaternion is given as follows:

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$$

This rotation matrix keeps the x-component unchanged, rotates the y-axis vector toward the $z-$axis and rotates the $z-$axis vector toward the negative $y-$axis. This is precisely the effect of a 90° rotation around the $x-axis$ in 3D Euclidean space. The reverse transformation gives the unit quaternion as follows:

$$q = (0.7071,0.7071,0,0).$$

This matches the original quaternion perfectly (apart from very small floating-point differences), confirming the correctness of both conversion algorithms.

Discussion and implications for education

The use of quaternions to represent and compute three-dimensional rotations provides not only a powerful mathematical framework but also valuable educational opportunities, particularly in the teaching and learning of geometry. The conversion algorithms between unit quaternions and rotation matrices explored in this study illustrate how abstract algebraic concepts can be made accessible and applicable in dynamic, real-world contexts. Such representations hold strong potential for enhancing students' spatial reasoning and conceptual understanding, which are critical for success in mathematics and STEM-related fields.

From an educational perspective, integrating quaternion-based modeling into geometry instruction aligns with current research emphasizing the importance of technology-supported and visually rich learning environments. For instance, studies by Taş and Yavuz (2023a) demonstrated that mobile instructional design positively influences students' perceptions of distance learning and mathematical engagement. Similarly, the development of the GeoHepta mobile application, grounded in the ADDIE instructional design model, has shown that students benefit from interactive, structured digital tools that make abstract mathematical content more concrete and meaningful (Taş & Yavuz, 2023b).

Moreover, the application of quaternions in teaching transformations directly supports the development of spatial abilities and geometric habits of mind, both of which are foundational in geometry education. The positive relationship between these two constructs has been confirmed in prior research (Taş & Yavuz, 2020), suggesting that students who engage with mentally demanding spatial tasks—such as rotating figures using quaternion logic also develop stronger habits of generalization, reasoning, and reflection in geometry.

In addition to cognitive outcomes, affective gains such as increased self-efficacy, interest in mathematics, and positive attitudes toward technology have been observed in students exposed to mobile and algorithm-based instructional approaches. The use of quaternions in visual programming environments or interactive simulations may similarly foster learners' confidence and motivation, contributing to a deeper, more personal engagement with mathematics (Taş & Yavuz, 2023c).

In conclusion, this study not only contributes to the theoretical discourse surrounding quaternion algebra and geometric transformation but also provides a bridge to its practical application in mathematics education. Future studies may explore the integration of quaternion-based tasks into secondary and tertiary geometry curricula, focusing on their impact on spatial reasoning, mathematical modeling skills, and technology-assisted learning environments.

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