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Using Augmented Reality to Teach Digital Literacy Course to Primary School Children with Special Educational Needs

Lyazzat Rakhimzhanova
Al-Farabi Kazakh National University, KAZAKHSTAN

Darazha Issabayeva*
Al-Farabi Kazakh National University, KAZAKHSTAN

Jaroslav Kultan
University of Economics in Bratislava, SLOVAKIA

Nazira Baimuldina
Almaty University of Energy and Communications, KAZAKHSTAN

Zhanylsyn Issabayeva
Abai Kazakh National Pedagogical University, KAZAKHSTAN

Zhamila Aituganova
Almaty Technological University, KAZAKHSTAN

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Abstract: Augmented reality technologies can create unique interactive learning environments for students with special educational needs that enrich the learning process and provide immediate feedback. This research analyzed the use of augmented reality in teaching digital literacy courses for primary school children with special educational needs. The study involved a quasi-experiment with participants using a mobile augmented reality application to assess its impacts on learning outcomes. The results showed the positive effects of augmented reality on student achievement. The results highlight the potential of augmented reality in inclusive education. In addition, the findings emphasize the importance of further research and development in this area and an increased use of augmented reality to improve the educational experience of students with disabilities. In light of the results, we conclude with recommendations for integrating augmented reality into educational programs and improving educational practices.

Keywords: *Augmented reality, digital literacy, digital content, inclusive education, primary school.*

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Introduction

In the age of digitalization, education has become a decisive factor for social integration and personal growth. Inclusive education deserves special attention in this context. The aim is to ensure equal access to knowledge for all students, including those with special educational needs (SEN). Digital literacy (DL), as a fundamental part of current education, should be accessible to everyone, regardless of individual characteristics.

In Kazakhstan, the teaching of computer science in primary school has changed. Since January 2022, computer science has been taught in first grade under "digital literacy." Previously, it was taught in third grade as information and communication technology. The development of the digital world and children's early use of gadgets make it necessary to acquire DL from an early age. The government has included the DL course in the curriculum to make its development as effective as possible, as stated in the Decree of the order of the Minister of Education and Science of the Republic of Kazakhstan (MESRK, 2020). Computer science educators are facing new challenges in teaching DL.

Recent technological advances have facilitated the use of smartphones and tablets in the classroom for children with SEN, as shown in the studies by Achmadi et al. (2012) and Kagohara et al. (2012). The development of various interactive AR learning environments with instant feedback in the research of Ajitha et al. (2022), Asatryan et al. (2023), Oleksiuk and Oleksiuk (2022), Shaltout et al. (2020), Theodoropoulos and Lepouras (2021), Chang et al. (2013), Yang and Chen (2010), Alkhabra et al. (2023) studied their effects on participants with SEN. These results demonstrate the potential of AR technology to create more engaging, interactive, and effective learning environments in various educational contexts, from anatomical studies to computer science education and even in inclusive education for children with SEN.

Visualizing teaching material in the DL course contributes to a deep understanding of computer technologies and their application in real-life projects, essential for modern, inclusive education. Such technologies help children with SEN learn

* **Corresponding author:**
Darazha Issabayeva, Al-Farabi Kazakh National University, Al-Farabi Avenue 71, Almaty, Kazakhstan. ✉ daraja_78@mail.ru

the material better through an interactive approach, making learning more accessible and interesting. However, the use of AR in primary school, including the possibilities of smartphone cameras and animations in textbooks, is still under-researched.

The authors have some experience working with groups of children with SEN and aim to provide findings that engage a more comprehensive range of teachers working with children with SEN in exploring the possibility of using AR to improve the quality of teaching.

The survey results have shown that many parents and teachers thought that the DL course did not engage children with SEN and did not bring noticeable benefits to them. Many respondents were dissatisfied with the methods and approaches used to teach children with SEN. In addition, the educational system does not sufficiently consider the individual characteristics and needs of children with SEN. Half of the respondents believed there are currently insufficient computer programs such as AR specifically designed for children with SEN.

There is a contradiction between the need to use AR in teaching children with SEN and the need for a better-developed application and methodology for teaching digital reality courses in primary school. For example, there are significant problems in teaching children with disabilities in Kazakhstan today:

- the course "DL" is not of interest to children with SEN;

- there are not enough computer programs aimed at personalizing children with SEN, for example, through the use of augmented reality (AR), which makes it difficult for these children to interact with and understand the educational material

- limited accessibility, as many educational resources and environments are not designed for accessibility, making it difficult for children with physical, sensory, or cognitive impairments to participate fully in educational activities.

The use of specially developed methods and teaching materials, as well as a mobile application with AR in the Unity 3D environment, can increase the interest of students with special needs in the DL course through new learning formats and high interactivity. AR applications personalize learning by adapting the content and pace to individual needs and providing audio description and text-to-speech support. Unlike virtual reality, AR applications work on smartphones and tablets without special equipment, making them more accessible in education. These applications accelerate the acquisition of DL by children with special needs and help them to learn equally. *"By stimulating augmented reality, these technologies provide children with straightforward techniques that help them to perceive and accept the real physical world. Understanding concepts is enhanced when AR and virtual reality (VR) are used in the classroom for children with special needs"* (Ajitha et al., 2022, p. 1). The article discusses the possibilities of AR to improve the quality of teaching for children of the following categories: Those with hearing impairments; Those with mental retardation; Those with musculoskeletal disorders; Those with severe speech disabilities, taking into account their typological characteristics.

This article aims to

-Identify and describe the specific benefits of AR in improving the accessibility and effectiveness of DL training for children with SEN.

-Assess the impact of AR on the academic performance and engagement of students with SEN in learning DL using quasi-experimental data and other evaluation methods.

-Present examples of using AR in the teaching process.

Literature Review

The DL education program must be tailored to each child's needs to ensure optimal learning. This is a basic requirement for inclusive educational institutions.

Kaffenberger (2021) shows that inclusive schools use a standard educational program adapted to each student's needs. Modifications to the educational program may include adaptations in time, materials, learning processes, and classroom management tools. This allows students to reach their potential and develop unique talents and abilities.

Using a Mobile Application with AR in Education

The developed mobile application corresponds to one of the five types of AR applications in education proposed by Yuan et al. (2021), such as object modeling, which helps students instantly obtain visual information about the appearance of a particular object from different perspectives. The resulting 3D models can be rotated, color-adjusted, and stylized to offer educational content from various perspectives. The research findings of Yuan et al. (2021) have shown that although AR cannot be used as a stand-alone learning tool like other forms of e-learning, it can help teachers transfer knowledge to students. In the context of inclusive education, AR tends to impact students positively and is liked by them. This suggests that AR can be helpful as a learning tool in inclusive education. RGB-D cameras enable the creation of customized learning materials, tracking and analyzing movements to adapt exercises, integrating adaptive technologies, controlling interfaces through gestures, developing interactive educational games, monitoring learning progress, supporting non-verbal communication, and analyzing social interactions in inclusive education. Students with mental disabilities (ID) may have difficulty completing everyday tasks, as studied by Yuan et al. (2021). Researchers Lin et al. (2016) believe that AR games can be an effective learning tool for students with mental disabilities.

Turan and Atila (2021) have shown that AR technology has an impact on supporting the learning of students with specific learning difficulties and that these students are willing to use AR technology because they find it attractive. Koti's (2023) study aimed to design, create, and evaluate AR to investigate its impact on the motivation and collaboration of secondary school students. It also explored the possibility of improving students' social and digital skills in an educational mobile learning scenario based on a situational approach. The author's main findings show that using AR materials successfully achieves the stated objectives, promotes skills development, is easy to use, and is positively received by teachers and students. However, design improvements and technical accessibility issues encountered during practical application are needed.

Murniarti et al. (2023) showed that AR cannot be used in schools like traditional e-learning tools. However, Koti's study (2023) can help teachers transfer knowledge to students. In inclusive education, students often assess the use of AR positively.

Teaching computer science in inclusive education

While there is a significant body of research (e.g., Baidrakhmanova et al., 2019; Balykbayev et al., 2021; Rakhimzhanova et al., 2019) showing how ICT can help schools and teachers to make their teaching more inclusive, there is a need for more evidence on how best to make computer science teaching itself inclusive. Shelton (2017) reviewed the literature on inclusive education in computer science lessons and identified many inclusive practices, including providing a relevant and authentic curriculum that focuses on depth of understanding, promoting culturally relevant tasks, and providing an inclusive environment that counters bias. The review also discussed what constitutes an inclusive computer classroom.

Pupils with SEN often face the risk of exclusion from computer science lessons. In the article, Ladner and Israel (2016) highlighted three aspects of this exclusion: teacher attitudes and expectations, pedagogical approaches, and accessibility. Students with SEN require unique resources or approaches to access the educational program. For example, students with visual impairments remain underrepresented in computing education. Promoting culturally relevant activities can be effective for students of all ages. Block-based programming languages such as Scratch have become increasingly common when students are introduced to computer technology. However, they may not be accessible to students with visual impairments Shelton (2017).

Inclusive practices used in all subjects (e.g., using Braille, providing orientation time, etc.) were complemented by computer science-specific approaches, such as using fully commented source code and setting up the screen reader to read all punctuation. These practices helped students solve complex problems.

Ludi and Reichlmayr (2008, 2011) proposed specific approaches to solving complex computer science problems using AR: fully commented source code and a screen reader configured to read all punctuation marks.

The approach proposed by Papazafiropulos et al. (2016) and colleagues involved 3D printing to create accessible computer science learning resources for students with visual impairments, including concepts such as data structures. They found that the resources they created were successfully used not only by sighted students but could also be used in inclusive classrooms.

The article of Huaman-Romani et al. (2023) examines the effectiveness of differentiated instruction in ICT in primary schools in Greece. The strategy of flexible grouping, the "thumbs up" method, and differentiated work schedules were particularly effective. However, asynchronous work combined with hierarchical learning activities has presented challenges for educators due to its complexity.

In the curriculum of the Republic of Kazakhstan for the course “DL,” one of the objectives is the training of computational thinking, as stated in the order of the MESRK (2020). Now, the question arises of whether there are difficulties in developing computational thinking for students with special needs. Mills et al. (2021) suggest that teachers can improve the problem-solving skills and critical thinking of students with special needs by integrating the following practices: Decomposition (breaking problems into smaller parts), Pattern Recognition (identifying patterns and trends), and Tool Selection (choosing the suitable computational devices).

Robotics is covered as part of the DL course in primary school, as stated in the order of the MESRK (2020). The study by Moșteanu (2021) examines the case of an eleven-year-old boy who is enthusiastic about technology, especially robotics. The authors use an experimental approach to improve his concentration by working with robotics, which impacts the educational process and overall development. The study shows that with age and becoming more interested in robotics, a boy’s concentration and psychomotor coordination improve, positively impacting the educational process and daily life. Robotics also promotes personal and educational development.

When developing the "DL" course, the article's authors followed Sternberg's well-known 7-stage problem-solving model. This model comprises the following phases: problem identification, problem definition, strategy building, information organization, resource allocation, monitoring, and evaluation of problem-solving (Sternberg & Grigorenko, 2003). These stages of the problem-solving process require a person to organize each step and make decisions simultaneously. In addition, the learner must gain experience and strength for the problem-solving process to continue accomplishing the task (Lin et al., 2016). Problem-solving skills have a potential impact on the independence and academic achievement of people with mental disabilities.

Erickson et al. (2015) and Root et al. (2017) used schema-based learning in the hands-on process of teaching problem-solving to students with mild mental disabilities, and these students can benefit from many learning features (Jitendra et al., 2015). Because of this result, visual representation is essential for special education students, as shown in the work of Root et al. (2017). Problem-solving processes involve some thinking strategies. The more common ones are algorithmic and computational thinking (Demir, 2021).

In another research, Liu and Phongsatha (2022) did not specify methods and technologies for improving the social participation of students with special needs. However, based on the context of their study, it can be commented that the following methods and technologies can be used to increase the social adaptation of children with special needs at school: the use of adaptive technologies and the introduction of technologies that help children with special needs in the educational process, as well as fostering cooperation between teachers, specialists, parents, and other participants in the educational process to create a supportive and inclusive environment. Research findings by Demirdag (2017) highlight the importance of inclusive education and the role of educational leaders and teachers in creating a supportive learning environment for all students, contributing to their successful learning and development.

The results of previous studies provide an essential basis for the present study, as they help to establish context and identify areas for further research. Their interrelationships are evident in the common themes, approaches, and methods. For example, several studies have highlighted the importance of an individualized approach to teaching children with SEN. Furthermore, the results of these studies help to highlight gaps and shortcomings in existing knowledge. As the results of previous studies are limited due to insufficient use of technology or a restricted focus on specific groups, this research can fill these gaps or extend the application of known methods.

Methodology

Research Design

The study's main methods included qualitative and quantitative approaches that help evaluate AR technologies' effectiveness and practical application in educational institutions. At the beginning of the quasi-experiment, we surveyed teachers and parents of children with SEN to identify existing problems of inclusive education in primary school.

During the implementation of the quasi-experiment, we conducted control tests to measure the extent of mastery of educational material on DL, as suggested by Issabayeva et al. (2022), in the control and experimental groups. The training took place in the latter using a mobile application with AR.

Following the quasi-experiment, we conducted interviews with the experimental group students and their parents (parents must always be present during the survey) to assess perceptions and attitudes towards using AR, which is a key stage of the study.

Sample and Data Collection

The main methods in the study included qualitative and quantitative approaches that help evaluate the effectiveness of AR technologies and their practical application in educational institutions. Qualitative methods were used: The first stage of the quasi-experiment involved questionnaires using Google Forms (see https://bit.ly/40cC0iL and https://bit.ly/3BLy4vh) to assess the level of motivation and engagement, observations, and interviews with teachers and parents to determine the initial level of motivation and engagement of students.

In the second stage, experimental and control groups of children were determined. The experimental group was trained using a mobile application with AR during the school year.

The control group was taught using the traditional method, which included standard DL lessons without AR. This method used printed teaching materials, oral explanations, and practical tasks on computers. It was based on the generally accepted teaching methods in primary schools and did not include additional digital or interactive technologies. Table 1 shows participants in the quasi-experiment with their demographic information.

Table 1. Sample of Study Participants

Diagnosed Special Educational Needs	Control Group		Experimental Group	
	Boy	Girl	Boy	Girl
Individuals with hearing impairments	1 (10 years)	2 (10 years)	1(10 years)	1(10 years)
Mental disabilities	1(10 years)	0	1 (10 years)	1 (9 years
Musculoskeletal disorders	1 (10 years)	0	0	1 (10 years)
Severe speech impairments	2 (10 years)	1 (10 years)	3 (10 years)	0
Total	5	3	5	3

Also, 5 teachers and 5 parents participated in the quasi-experiment. The intervention lasted for eight weeks (see Table 2). During this time, the experimental group used the AR application in each DL lesson, which was approximately 45 minutes once a week. The duration and intensity of the intervention were the same for all participants.

The AR application was developed to support teaching a DL course. The mobile application was created using the ADDIE methodology. At the analysis stage, the most valuable and important aspects of DL were identified according to the needs of SEN. The educational courses were designed to integrate AR to facilitate children's understanding of the material. We created content that included AR elements, such as 3D models, interactive components, virtual educational materials, and game tasks adapted for children with SEN. We implemented the AR course into the educational process, with support and instructions for teachers and parents. When assessing the effectiveness of using AR in teaching DL, both academic results and the impact on the motivation and involvement of the participants were considered.

The app was integrated into the curriculum so that each complex definition and essential information was supplemented with AR activities to allow students to understand better and master digital terms. The app included audio instructions, a cognitive assistant, and visual elements to make them accessible to children with hearing, speech, and mobility impairments. The control group followed the traditional program (Platform of electronic textbooks and books i-book). Table 2 shows the curriculum of the "DL" course.

Table 2. Parts of "Creativity and Computer" in *Digital Literacy Course*

№	Lesson Topics	Learning Objectives	Number of Hours
1	We continue to develop the program	2.4.1.1 develop a branching algorithm in a gaming programming environment (Scratch) according to a given scenario;	1
2	Execution of the algorithm	2.4.1.2 implement the branching algorithm specified in verbal form in the game programming environment (Scratch);	1
3	Create your own character	2.4.2.1 create a character in the built-in graphic editor of the game programming environment (Scratch) for the project; 2.2.2.1 copy and reflect the character's figure in the built-in graphic editor of the game programming environment (Scratch) for the project; 2.2.2.2 edit the character's figure (trimming, rotating, resizing) in the built-in graphic editor of the gaming programming environment (Scratch) for the project;	2
4	Project work	2.4.2.1 create a character in the built-in graphic editor of the game programming environment (Scratch) for the project; 2.2.2.1 copy and reflect the character's figure in the built-in graphic editor of the game programming environment (Scratch) for the project; 2.2.2.2 edit the character's figure (trimming, rotating, resizing) in the built-in graphic editor of the gaming programming environment (Scratch) for the project.	1

The authors of this paper developed a website https://specialdw-children.kaznu.kz/ and a mobile application with AR to teach DL to children with SEN. AR elements were integrated into the teaching content of the course, which provides students with basic knowledge, skills, and abilities in the areas of computer design, presentation and processing of information, working on the Internet, computational thinking, and robotics for effective use of modern information technologies in practice.

The effectiveness of AR in inclusive education is illustrated by the seamless interaction between a mobile application and website content, which improves the accessibility and engagement of learners with diverse needs (Figure 1).

Figure 1. AR While Studying the Digital Literacy Course

As an application of AR, the lessons offered short video blocks to visually represent the learning material, definitions with drawings highlighted when hovered over, interactive tests and practical tasks, and workbooks with touch control functions. Figure 2 shows a block diagram of the mobile application with AR elements.

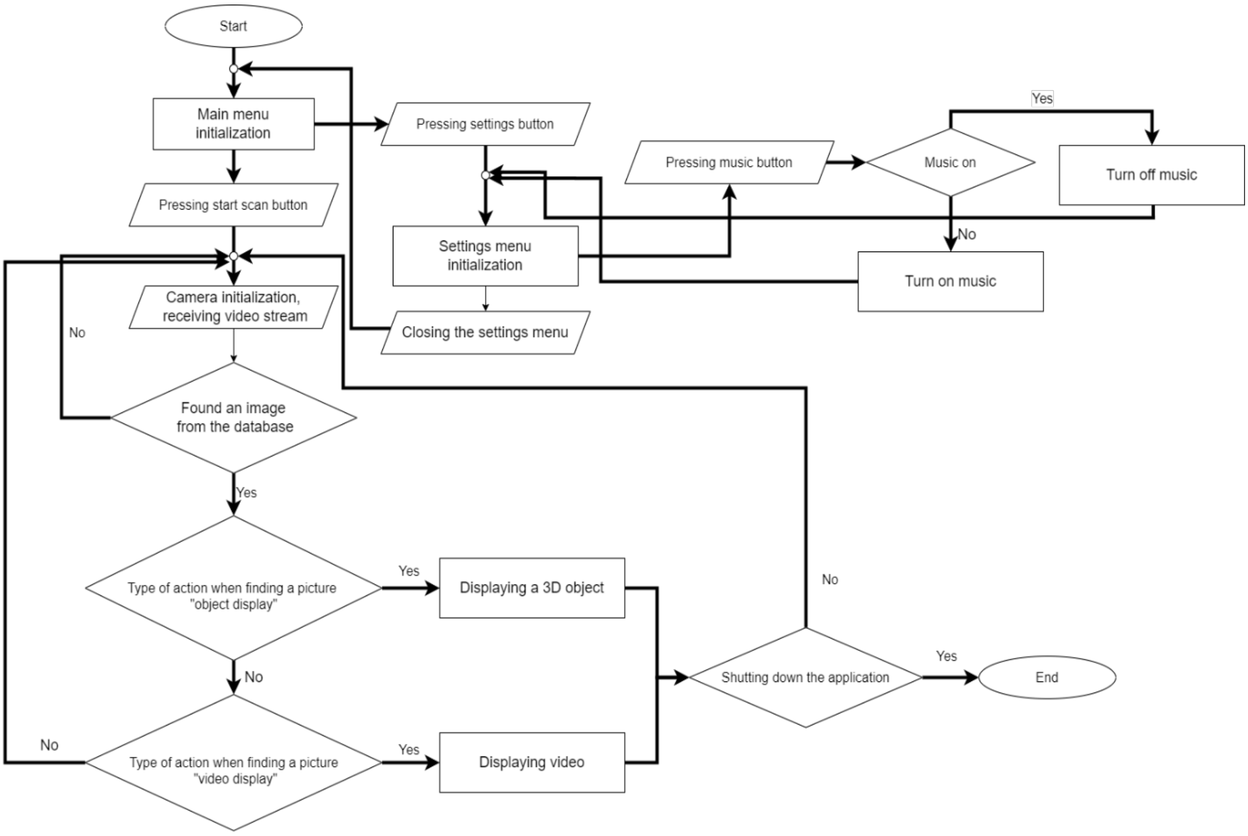

Figure 2. Flowchart of a Mobile Application with AR Elements

This training was tested through testing and questioning of parents and teachers. The study demonstrates that using AR can significantly improve the interaction and learning of students with SEN. AR provides more interactive and personalized learning experiences, which enhances understanding and learning for students with diverse learning needs, as shown in the studies of Akhmetova et al. (2022), Eliseeva and Ersarina (2019), Ospankulov et al. (2022).

Individualization of Training:

Studies of children for each of the four categories are presented under this title. A corresponding graphic icon was installed for each group of health limitations, allowing the child to navigate through materials adapted to his abilities (see Figure 3).

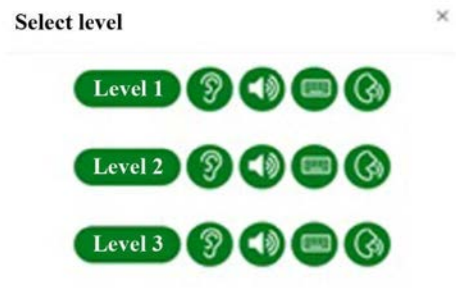

Figure 3. Example of Graphic Symbols for Children with Different Talents.

Child 1 (C1): General data (Age: 10 years, Diagnosis: Sensorineural hearing loss of high degree). C1 studied in a regular school with support for inclusive education. He used a hearing aid and services from a deaf teacher. The teacher used visual cues and adapted educational materials, adding subtitles and signed translations to video lessons, tests, and practical tasks in the mobile application to improve his learning for DL courses using AR. The child received information through visual means and practical activities.

He was comfortable completing the tasks individually as C1 feels isolated, especially in group situations with noise while using a hearing aid and without adequate support. C1 solved mathematical and logical problems in the programming section and showed above-average results.

Child 2 (C2): General data (Age: 9 years, Diagnosis: Moderate mental retardation). C2 used simple phrases to communicate and might need extra time to articulate his thoughts. Although his verbal skills were limited, he actively used nonverbal communication, such as gestures and facial expressions, to express his feelings and needs. C2 exhibited increased emotional sensitivity and reacted to stress or environmental changes more intensely than his peers. The educational materials were presented in small portions and gradually became more complex (Figure 3); methods included complex tasks to facilitate through multi-level test questions, clarity-picture plans, graphic models, assistance performing certain operations, and samples of problem-solving. To prevent rapid fatigue, children's attention switches from one activity to another, and various activities are offered. Didactic material and game moments supported C2's interest in classes and emotional mood. The site had sound accompaniment for each definition, practical task, and test with the ability to adjust the speed and sound.

Child 3 (C3): General data (Age: 10 years, Main problem: Congenital anomalies of the spine). C3 studied in a comprehensive school where a program to support children with physical disabilities was available. The school had ramps, lifts, and adapted toilets, allowing her to move freely around the building. C3 actively communicated orally and in writing and used a virtual keyboard and two keys on a regular keyboard (1-Yes/2-No) to make writing and completing DL course assignments easier. C3 exhibited high tolerance and a positive attitude toward AR use. C3 showed his passion for computer science, where he often stood out for her achievements.

Child 4 (C4): General data (Age: 10 years, Diagnosis: Severe speech impairment associated with dysarthria). C4 studied in a class with a general education program. The school was equipped with special technological tools to assist in learning. Due to his speech limitations, C4 used alternative and augmentative communication tools, such as tablet-based communicators and specialized text input programs, to enable him to actively participate in the learning process and communicate with classmates and teachers. C4 demonstrated strong analytical skills, especially in the field of computer science. He was well versed in logic programming and computer problem solving, making him an excellent student in technology subjects. The mobile application was well-organized tasks, from straightforward to complex tasks (Figure 8). C4 more easily perceived tasks with 3D images available in the mobile application.

Practical Application: The article presented case studies that show how specific AR applications improve educational outcomes. Including real-life examples makes the discussion more visual and understandable, allowing educators to understand better how these technologies can be adapted to their needs.

The first and second stages of the research involved qualitative methods, and the subsequent stages involved quantitative research methods.

In the third stage, students in the experimental group used the author's adapted digital textbook using an AR mobile application. The AR mobile application was designed to enhance the learning process by providing interactive and immersive content. Following a traditional educational approach, students in the control group used a digital textbook without AR features. The results of the tests conducted after the course were collected. These data included scores that reflected the students' knowledge and skills. Table 3 shows the criteria for obtaining scores.

Table 3. Evaluation Criteria for Grade 2 in the Course "Digital Literacy

Paragraph Title	First Level (0-49)	Average Level (50-74)	Advanced Level (75-89)	High Level (90-100)
§ 5. Branching Algorithm	- Understanding of basic branching concepts. - Ability to create a simple algorithm with one condition.	- Development of a branching algorithm with several conditions. - Application of the algorithm in a simple problem.	- Creation of a complex branching algorithm with nested conditions. - Optimization of the algorithm for efficient execution.	- Development of a complex algorithm that includes several levels of conditions. - Integration of the algorithm into the overall project.
§ 6. We Continue to Develop the Program	- Perform basic steps to continue program development.	- Adding new functional elements to the program.	- Optimization and improvement of existing program functions.	- Development of new complex functions and their integration into the program.
§ 7. Creating Your Own Character	- Creating a simple character in a graphic editor.	- Character detailing using various editor tools.	- Create a unique character with animation and detailed elements.	- Development of multiple characters with unique traits and interactions.
§ 8. Project Work for the Quarter	- Completing a simple project with basic elements.	- Development of a project using several functions and elements.	- Creating a complex project with multiple characters and interactions.	- Development of a completed project with original ideas and optimization.

The study used specially developed tests and questionnaires to assess participants' levels of DL. These tools were adapted to the participants and tested for reliability and validity using pilot testing.

When the tests were evaluated, we used the content validity method. This method does not have a strict mathematical formula. Based on expert opinion, we assessed how well the test covers all aspects of the measured cognition. We assessed the factors influencing students' DL based on data on several variables: text processing skills, Internet skills, critical thinking, and software knowledge. Factor analysis revealed two variables (factors): "technical skills" and "information literacy." The factor analysis results showed that students' DL has two key factors. *Technical skills* focus on students' ability to operate tools and software, while *information literacy* involves the ability to process and critically evaluate information effectively.

We conducted pilot testing before and after the course to evaluate student knowledge and skill improvements. We collected and analyzed quantitative data from testing and educational activities in the fourth stage.

Analyzing of Data

The results were analyzed statistically, and the main parameters were analyzed.

When conducting a t-test, we checked whether the average score of the two groups differed. Accordingly,

- We collected assessment data for both groups (Table 4).
- We calculated means and variances for each group.
- The t-test formula (temp) was applied to two independent samples.
- Compared the calculated t_{emp} value with the critical value (t_{crit}) from the table:
  - The experimental group using AR received higher grades, with an average of 84.25%, compared to the control group, which received 71.63%. This performance difference is shown in Table 4. It suggests that, in general, AR increases academic performance.
  - The standard deviation of the results achieved by the experimental group is 4.03, compared to 3.93 for the control group, as shown in Table 4. Based on these data, the experimental group's results are much scattered (heterogeneous) compared to the control group's. Some students got much better results due to the introduction of AR.
- Accepted the null hypothesis based on the result: But based on calculating the significance criterion of the t-test results (equation (3)), it is possible to confirm the alternative hypothesis (H1) that students in the experimental group show, on average, a higher level of knowledge. The empirical value t_{emp} = 6.35 (data from the *t*-test calculator [http://surl.li/fquxgf]) obtained in the experiment exceeds the critical values of the student's t-test t_{crit} = 2.145 [tabulated value, http://surl.li/kdfpvt]. 6.35>2.145; therefore, there is reason to accept the alternative hypothesis (H1) that students in the experimental group show, on average, a higher level of knowledge.

We used ANOVA to compare the means between the three groups. The analysis of variance (ANOVA) method was chosen for data analysis for the following reasons. Firstly, the study aimed to compare the means of the dependent variable between several groups. Secondly, ANOVA avoids increasing the probability of type I error when conducting multiple pairwise comparisons using *t*-tests. ANOVA considers the variation within and between groups, providing more accurate and reliable results when analyzing differences between multiple groups. The ANOVA results indicate that using AR in the DL course has different impacts on learning outcomes. Necessary preliminary tests (Shapiro-Wilk and Levene tests are shown in Table 4) were performed to check that the data met the assumptions required for the correct analysis use.

Table 4. Statistical Test Results

Test	Statistic	*p*-value
Shapiro-Wilk (Group 1)	0.96	0.85
Shapiro-Wilk (Group 2)	0.99	0.98
Shapiro-Wilk (Group 3)	0.98	0.97
Shapiro-Wilk (Group 4)	0.97	0.92
Levene Test	0.49	0.68
ANOVA	22.3	0.45

The null hypothesis (H_0) is not rejected because the result is a p-value > .05 in all groups, i.e., the data for all four groups are normally distributed. Thus, the normality assumption for ANOVA analysis is met based on the results of the Shapiro-Wilk test.

Results

Pedagogical Experiment

A pedagogical experiment assessed the impact of AR on teaching DL. This experiment involved comparing two teaching methods: one that used AR technology and a control one conducted without AR. The experiment aimed to test and evaluate the effectiveness of the proposed educational methodology for teaching DL to the participants using AR.

Ascertaining Experiment

The first stage of the experiment was a confirmatory experiment in which the questionnaires using Google Forms are shown in Figure 4 and Figure 5; a survey, a conversation, and videoconferences were conducted with teachers and parents of children in primary schools of inclusive education in the Republic of Kazakhstan, which allowed a more detailed study of this issue based on the questions asked. The study involved 105 teachers and 80 parents.

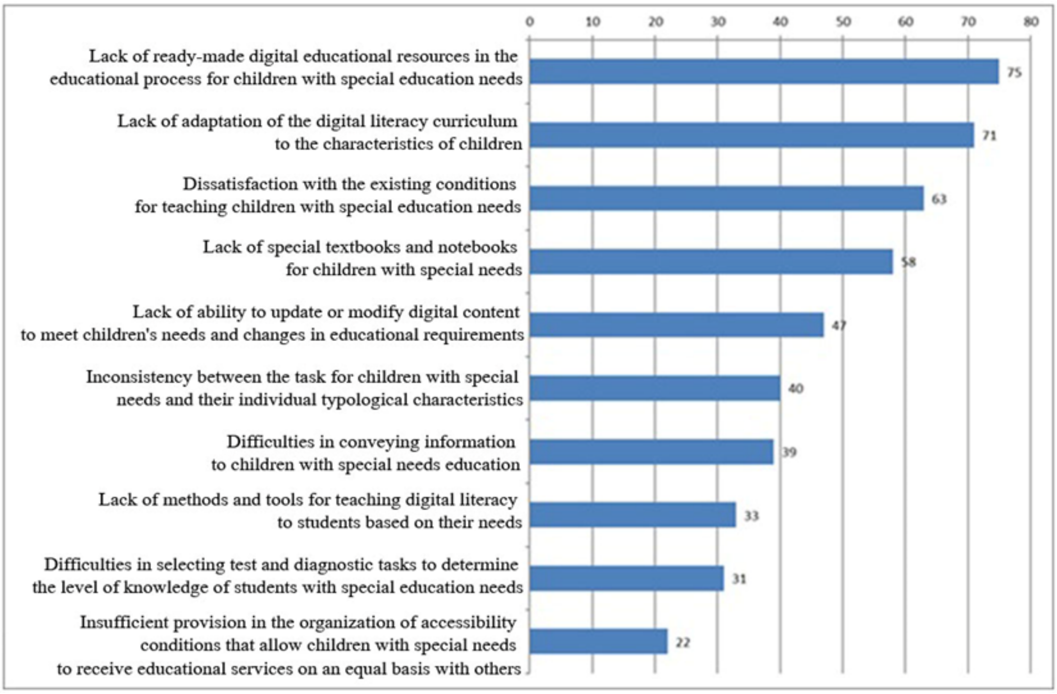

Figure 4. Survey Results of Primary School Teachers in Inclusive Education in the Republic of Kazakhstan

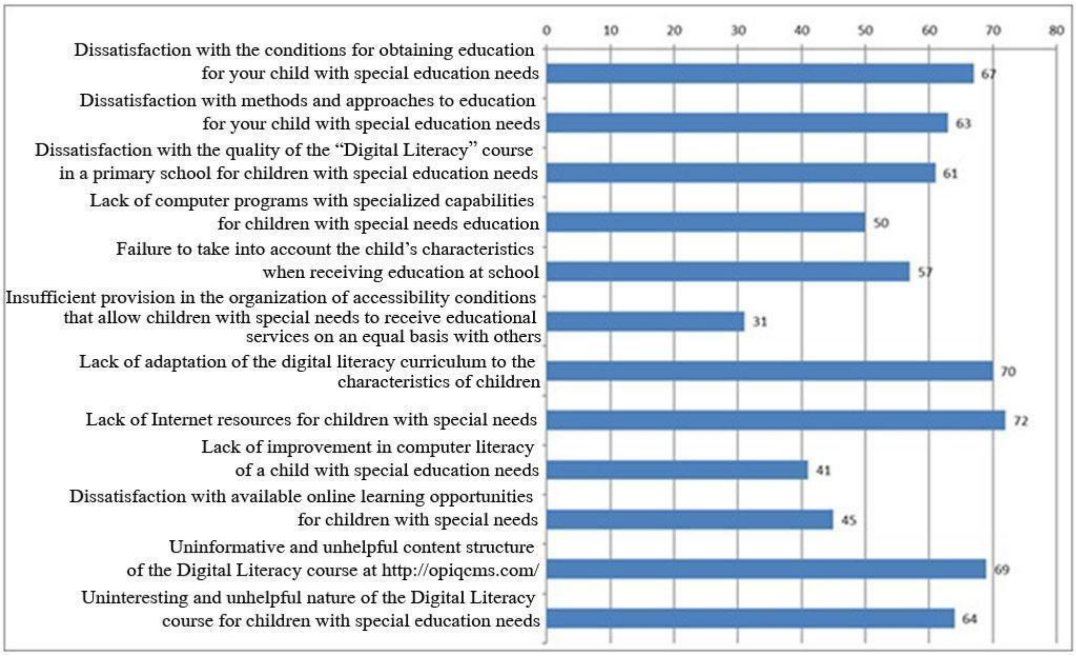

Figure 5. Parent Survey Results of Children in Primary Schools of Inclusive Education in the Republic of Kazakhstan

The survey results showed that most respondents expressed concern about limited access to Internet resources that would be adapted to the needs of children with disabilities. Most respondents noted the need to adjust textbooks to consider the characteristics of the participants. Many parents believe that the content of the DL course on this web resource is not informative and does not meet the needs of children with SEN. A significant number (67%) of parents expressed dissatisfaction with the conditions in which their children receive education, highlighting the lack of adaptation and support. Some respondents (61%) noted that the DL course does not stimulate the interest of children or does not benefit their educational process. Many respondents (63%) expressed dissatisfaction with the methods and approaches used in teaching children with SEN. A significant number (61%) of parents believe that the quality of teaching in the DL course at the primary school level leaves much to be desired. Some parents (57%) noted that their children's individual characteristics and needs are not sufficiently taken into account in the education system. Half of the respondents believe there are insufficient computer programs with specialized capabilities for children with SEN. About half of the respondents expressed dissatisfaction with the Internet's availability of educational opportunities. Some parents believe the teaching of computer literacy is ineffective. Some respondents pointed to insufficient accessibility conditions that would allow children with special needs to receive educational services equally with others.

The results show that the educational system has a number of serious problems and disadvantages related to the education of children. These problems include a lack of resources using modern technology and limited access to educational opportunities.

Thus, the currently used digital textbook of DL was integrated with AR by projecting and introducing any virtual, imaginary objects onto real space (on the screen of a computer, phone, or similar device), which helps to simulate complex three-dimensional shapes.

Formative Experiment

The data was collected through student tests. The test results were collected from teachers of Kazakh primary schools that support inclusive learning (Municipal State Institution "School-Gymnasium No. 5", "Comprehensive School No. 57", "Comprehensive School No. 129", "Comprehensive School No. 49"). We used the following statistical tests.

t-test

Initially, we developed content for the 1st part and interactive assignments with and without AR (Textbook, website). The educational materials used by both groups were identical in content. However, the difference was that the experimental group was trained using the mobile application with AR components, added sign language translation, voice guidance, keyboard use, text enlargement, and drawings on the screen. The control group studied using an existing digital textbook without AR components. We formed a sample of students from four categories: people with hearing impairments; persons with mental retardation (MDD); persons with musculoskeletal disorders; persons with severe speech impairments. Both educational materials were implemented within a certain period (1st quarter). Students' progress was regularly monitored, and necessary support was provided to ensure the quality of the curriculum delivery. Quantitative analysis methods were used, using statistical methods to compare test results to determine statistically significant differences between groups.

Table 5 demonstrates the results of the experimental and control groups. In addition, they are presented in Figure 6. Teachers collected the test results in both groups. Students: $St_1, St_2, St_3, St_4, St_5, St_6, St_7, St_8$; n- number of students; σ - Standard deviation.

Table 5. Test Results for Each Group (Measured on a 100-Point Scale)

Groups	**St_1**	**St_2**	**St_3**	**St_4**	**St_5**	**St_6**	**St_7**	**St_8**	**Mean Value**	**σ**
Experimental group with AR (pre-test)	65	66	70	68	63	67	69	66	66,75	2,53
Experimental group with AR (after the course)	80	82	90	85	78	85	88	86	84.25	4.03
Control group without AR (pre-test)	64	62	66	63	61	65	64	63	63,5	1,66
Control group without AR (after the course)	77	68	74	65	75	73	71	70	71.63	3.93

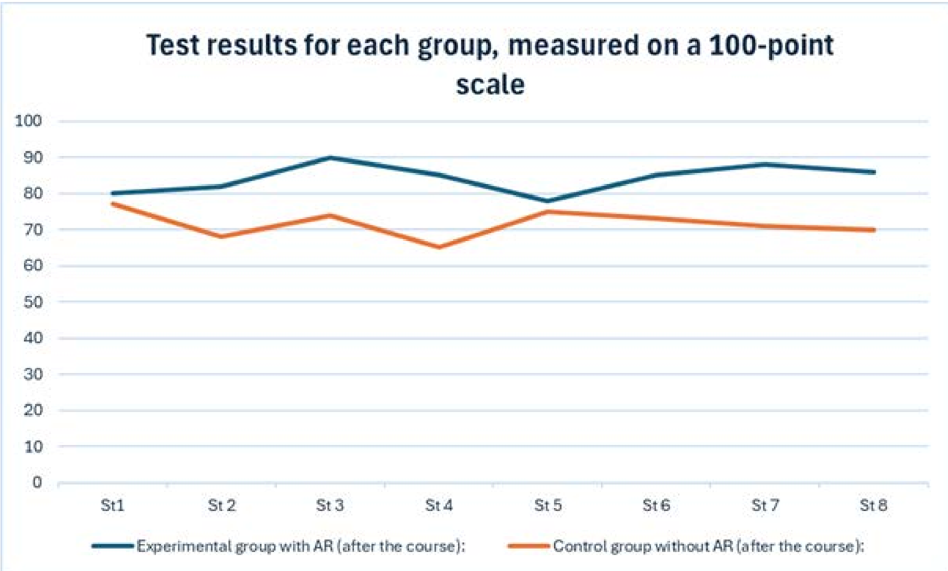

Figure 6. Diagram of Test Results for Each Group (After the Course)

Null hypothesis (H_0): The students' knowledge in both groups is, on average, the same. Alternative hypothesis (H1): Students' knowledge in the experimental group differs from that of students in the control group.

A two-sample t-test was conducted to compare the mean outcomes between the two groups (St_1–St_8). The results indicated a statistically significant difference between the groups, $t_{emp} = 6.35$, $p < .001$, with the mean difference between the groups being 12.62 (95% CI [8.36, 16.89]). The effect size, calculated using Cohen's d, was $d = 3.18$, indicating a large effect size. This suggests that using AR substantially positively impacted students' learning outcomes.

Analysis of variance (ANOVA) was used to assess the differences between the means of three or more groups. Table 6 shows the test results of four different groups.

Table 6. Test Results for Groups with Different Special Educational Needs

Groups	T1	T2	T3	T4	T5	*F*	*p*	ANOVA Effect Size
Group 1 (individuals with hearing impairments)	82	88	85	90	84	22,36	5.75×10^{-6}	0.807
Group 2 (mental disabilities)	78	74	80	85	81			
Group 3 (musculoskeletal disorders)	88	92	90	93	95			
Group 4 (severe speech impairments)	75	78	77	80	76			

The results show significant differences among the groups. Group 3, representing individuals with musculoskeletal disabilities, demonstrated the highest results on all tests, while Group 4 (individuals with severe speech impairments) demonstrated the lowest results. This may indicate the need for additional support for Group 4 during the testing process. The F-statistic value of 22.36 suggests significant differences between the mean scores. The *p*-value is significantly less than the standard threshold for statistical significance (0.05), which allows rejecting the null hypothesis that all groups have the same mean values. This means that statistically significant differences in the mean test scores exist between at least two of the three age groups. The ANOVA effect size value (about 81% of the variance in learning outcomes) shows significant differences between groups. The ANOVA results indicate that using AR has a different impact on learning outcomes depending on the kind of students diagnosed with SEN.

Table 7 shows the results regarding the reaction of participants to the educational content of the website and mobile application.

Table 7. Results regarding the Reaction of Children with SEN to Educational Content of a Website and Mobile Application with AR

Educational Content Criterion	Reaction of Children with Special Needs
Clarity and structure of the material	I understand in assimilating information, minimizing the possibility of confusion.
Interactivity	Promotes active participation, maintains attention and increases motivation.
Individual adaptation	Allows to customize the complexity and pace of the content provided, which is critical for children with different educational needs.
Visual and auditory support	Provides support through multimedia, which is important for children with difficulties in reading and comprehension of text.
Feedback and encouragement	Helps children understand their progress and encourages further learning through positive reinforcement.
Accessibility and ease of use	Ensures that the application can be used by children with different physical and cognitive limitations.
Content Security	Eliminates exposure to obscene or inappropriate material, creating a safe learning environment.

AR technology enables the creation of customized learning environments tailored to students' specific needs. This applies not only to children with physical and sensory disabilities but also to students with cognitive impairments.

Discussion

The study's primary results show that using AR in the inclusive educational process positively affects students' academic performance. In addition, the analysis showed that, despite the higher average academic performance, the experimental group's results were more heterogeneous, which indicates the heterogeneity of AR's impact on different students. Nevertheless, the overall positive effect confirms the feasibility of introducing AR into the inclusive education process.

The results demonstrate the positive impact of using AR on academic performance. AR was particularly effective for several reasons. First, AR provides the ability to create multimodal learning environments that integrate visual, auditory, and tactile elements, which is important for students with different learning disabilities. For example, for students with hearing impairments, AR provides visual cues and animations that can replace or complement auditory information. AR reduces physical stress through virtual interactions for students with mobility impairments by making learning more accessible. Students with intellectual disabilities can benefit from the interactive and gamified elements of AR, which maintain motivation and make complex concepts more accessible. Secondly, AR facilitates the individualization of learning as the content can be tailored to the individual needs of each student. This is particularly important for students with SEN, as they often require specialized educational programs and approaches. AR also allows students to work at their own pace, review material as needed, and receive immediate feedback, which helps them retain knowledge more deeply.

The results are consistent with those of several previous studies. In particular, Koti's (2023) and Lin et al.'s (2016) studies also confirmed that introducing AR technologies improves academic performance and increases student engagement. Our findings indicate a stable trend in using AR as an effective tool in the inclusive educational process.

However, unlike the studies by Alkhabra et al. (2023), Liu and Phongsatha (2022), and Mills et al. (2021), where the impact of AR on critical thinking development was insignificant, our data show a more pronounced improvement in this aspect. A possible explanation for this discrepancy may lie in differences in methodology and participants. For example, the studies by Alkhabra et al. and Mills et al. used different age groups or different content, which could have affected the results. The duration of AR use in the educational process could also have an additional influence.

Thus, the findings are generally consistent with those of previous studies but reveal certain discrepancies that may be due to differences in approaches and research contexts.

The results confirm the theoretical premise that using AR in the inclusive educational process can significantly improve the quality of learning for children with SEN. From a theoretical point of view, the results confirm the cognitive learning theory, according to which interactive and visually rich technologies, such as AR, contribute to a deeper assimilation of material. This research's results also contribute to the development of research in inclusive education, expanding the understanding of how new tools can be integrated into curricula to achieve higher academic results in primary school.

From a practical perspective, the study results show that implementing AR can effectively improve students' academic performance with SEN, especially in DL. However, it is worth noting that the higher variability of results in the experimental group indicates heterogeneity in the perception of AR by students with SEN. This may be due to individual differences in cognitive styles, motivation levels, physical abilities, or basic knowledge of students with SEN. Such heterogeneity requires further research to identify factors that influence the effectiveness of AR use and to develop more individualized approaches to implementation.

The significant variation in academic performance in the experimental group was unexpected, which may indicate that AR is not equally effective for all categories of students with SEN. A possible explanation for this phenomenon could be the difference in the potential abilities of children with SEN in the corresponding categories (the study included students with hearing impairments, mental disabilities, musculoskeletal disorders, and severe speech impairments). The results show that further research is needed to optimize the methods for using AR in the classroom, considering the individual typological characteristics of children with SEN.

Thus, our results highlight AR's significant potential in inclusive education and the need to study further the factors influencing its effectiveness. The study has important practical and theoretical implications for developing educational technologies and teaching methodology. From a practical point of view, the proven positive impact of AR on the academic performance of students with SEN opens up new opportunities to improve the quality of inclusive education. The introduction of AR into the educational process can be an effective tool for increasing the motivation and engagement of students with SEN, especially when studying complex and abstract disciplines such as DL. This study can form the basis for developing new curricula focused on AR and encourage educational institutions to use innovative technologies more actively.

From a theoretical perspective, the study's results expand the existing understanding of the impact of digital technologies on learning and support the hypothesis that interactive and visually rich environments contribute to better learning. In addition, the identified heterogeneity in the impact of AR on students with SEN indicates the need for further study of individual differences in the perception of technology. This may lead to the development of more flexible and adaptable educational strategies that consider the needs of different groups of students.

Therefore, this study's results may significantly impact teaching practices and the theoretical foundations of using technology in education, contributing to the creation of more effective and inclusive learning environments.

Overall, the discussion highlights the importance of innovation in education and the ability of technologies such as AR to transform learning for children with SEN by making it more accessible and effective for all students.

Conclusion

In conclusion, using AR in the classroom for primary school children with SEN is essential. The results show that using AR in teaching DL significantly impacted the participants' learning outcomes. When using a mobile application for smartphones and tablets with AR elements, the following features are provided in the mobile application to support teachers and students:

- demonstration of dynamic and interactive three-dimensional models of the learning material;

- manipulation of virtual objects with the help of hand gestures and their use to improve the feeling and determination of the size, shape, and position of objects;

- displaying various additional information about the object on the screen;

- using the built-in smartphone cameras to show animated figures directly in the textbooks on the required pages (e.g., the use of fairy tale discourse, i.e., polysemantic symbolic images and metaphors of fairy tales, a fairytale-like narration of the educational material).

Data from a pedagogical experiment confirm the hypothesis that AR positively affects students' learning outcomes. The strong positive correlation between time of AR use and grade improvement underscores the potential value of integrating AR technologies into educational programs. These findings may provide a basis for further expansion of research in this area and the development of educational programs incorporating AR to improve educational effectiveness.

The main contribution of this study is to provide empirical evidence of the effectiveness of the use of AR in inclusive education and to identify areas for future research that will help optimize and expand the use of this technology. The results of the study can serve as a basis for further developments in the field of educational technologies and contribute to a broader implementation of AR in the educational process, which will ultimately lead to an improvement in the quality of inclusive education and the development of new teaching methods for the DL course in primary school.

Recommendations

In light of the results, we suggest several specific recommendations:

- Researchers should expand AR content to create tailored modules that consider the needs of students with SEN. Visual modules should contain animations, infographics, and text cues for students with hearing impairments. Modules should include minimal physical effort, using eye tracking or voice commands for students with musculoskeletal impairments. Modules that use interactive elements and AR tasks that simulate real-life scenarios can increase motivation and engagement for students with cognitive impairments. We recommend modules with game-like features, such as reward systems, progress bars, and virtual achievements.

- To provide intuitive navigation and interaction, improving accessibility and ease of use through improved interfaces and device compatibility is critical to ensuring widespread adoption of AR technologies among diverse groups, particularly for students with motor or cognitive disabilities.

- Additional courses, seminars, and training programs for teachers' professional development should be organized.

- Adaptive AR applications should be developed considering each student's knowledge level and preferences. AR tools should allow students to move at their own pace and include modules that allow them to repeat complex topics.

Collecting regular feedback from students and teachers is key to continuously improving AR content and enhancing its educational impact.

These recommendations should be applied mainly to learners with special educational needs and provide actionable steps to ensure that technology meets the diverse needs of all learners.

Limitations

The present study has several limitations that could affect its generalizability. First, the participants were limited to a specific age group and academic discipline, which may limit the generalizability of the findings to other age groups or subjects. Future studies should include more diverse student groups and disciplines.

Second, the study was conducted in a controlled learning environment that may not reflect real-world educational practice. Future studies should conduct experiments in more natural learning environments to increase the external validity of the results.

In addition, due to the limited duration of the study, it was not possible to assess the long-term effects of AR on the academic achievement and cognitive development of students with disabilities. Future studies should conduct long-term follow-up studies to assess the effects of AR on DL.

Finally, the influence of additional factors, such as students' technical skills or equipment availability, was not sufficiently investigated. This limitation requires further analysis to examine the results of implementing AR in the educational process.

Future studies should improve the generalizability and validity of the results by increasing the number of participants, using more naturalistic environments, extending the duration of the study, and considering additional factors that influence the effectiveness of AR in the classroom.

Finally, the present study's analysis focused exclusively on students with SEN between grades 1 and 3 who gave written informed consent to participate in the research.

Ethics Statements

The studies involving human participants were reviewed and approved by Al-Farabi Kazakh National University (protocol number IRB - A510). All participants gave written informed consent to participate in this study.

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Authorship Contribution Statement

Rakhimzhanova: Conceptualization, design, analysis, writing, supervision, concept and design, data acquisition, data analysis, drafting manuscript, critical revision of manuscript. Issabayeva: Editing design, analysis, writing, concept and design, data acquisition, data interpretation, drafting manuscript, critical revision of manuscript. Kultan: drafting manuscript, critical revision of manuscript, statistical analysis. Baimuldina: Data acquisition, drafting manuscript, technical or material support. Z. Issabayeva: drafting manuscript, technical and material support. Aituganova: Data acquisition, drafting manuscript, technical and material support.

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