(Online) ISSN 2303-4521
Periodicals of Engineering and Natural Sciences *Original Research*
Vol. 13, No. 3, August 2025, pp.671-680

Interactive learning in the digital age: Advancing STEM skills in primary school education through robotics

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ABSTRACT

The purpose of the study is to analyze the effects of using robotics as elements of interactive learning on the development of STEM competencies in primary school students. The study is of the quasi-experimental-comparative type, the duration of the intervention (6–8 weeks), the assessment tools (test, questionnaire), and the statistical analysis (t-test). The main instruments: questionnaires, a STEM competency scale adapted for children, a didactic experiment based on observation (with the involvement of two groups of schoolchildren - 26 participants in the control group and 26 participants in the experimental group). The study showed insignificant changes in the level of STEM competencies in the control group, which studied according to the traditional program without the use of robotics: the increase was only 0.6 points (from 11.5 to 12.1), which is not statistically significant ($p = 0.11$). However, participants in the experimental group, who studied with the use of robotics, showed a statistically significant improvement in STEM competencies - the increase was 4.1 points (from 11.8 to 15.9), ($t = 6.74$; $p < 0.001$). This indicated a pedagogical effect and an increase in the practical component of learning. The conclusions noted that there was an increase in the general level of knowledge of students and their practical skills, which was accompanied by an increase in students' self-confidence and desire to solve atypical tasks. Therefore, the study fills the existing empirical gap in assessing the effectiveness of STEM education using robotics in primary education and has the potential to be scaled up in other educational institutions.

Keywords: Robotics, STEM education, Competencies, Digitalization, Technologies

1. Introduction

In the modern digital era, pedagogical approaches have undergone significant transformations that take into account the growing demand for interactive teaching methods, in particular by ensuring the active participation of students in the cognitive process. The proposed model of education seems relevant in the context of further progress in the use of technology, since it will generally contribute not only to basic academic knowledge, but also to the growth of key competencies in the realities of the 21st century [1]. Among many educational areas, STEM education (a combination of science, technology, engineering and mathematics) now occupies an important place, helping students develop systemic thinking, the ability to critically perceive information, solve various problems and act collectively, using the knowledge and practical experience gained [2]. For primary school, STEM education has a very specific content, since the foundations of cognitive activity are formed at an early age, and interest in natural and technical sciences develops, including the first skills of working on projects or conducting their own research. An important part of modern STEM education is educational robotics [3]. Such a tool aims to combine the use of gaming and educational approaches, providing opportunities for modeling or experimentation, which at the same time promotes critical thinking. However, despite the rapid development of digital robotic technologies, there are no comprehensive answers among scientists regarding the effectiveness of integrating robotics into the educational process of primary education.

The current gap in research is the lack of empirical studies that, based on experimental methods, assess the impact of robotics on the formation of STEM competencies of primary school students. Moreover, the current problem is the lack of empirical evidence of the impact of robotics on the evolution of education and STEM technologies, the acquisition of relevant competencies in primary school students. The importance of such technologies for middle and high school has been proven and repeatedly emphasized, while the existing gaps in understanding the impact of such tools on the education of primary school students are obvious. Accordingly, there is a need not only to identify such a scientific gap, but also to propose certain experimental results that would be aimed at analyzing changes in the formation of STEM skills in elementary school students, in particular by integrating robotics into the educational process. This study aims to fill these gaps by comparing the effectiveness of a modern STEM program and a program with the integration of robotics. Therefore, the novelty of the study lies in combining quantitative analysis of learning outcomes with students' self-assessments using adapted STEM competency scales, which will allow for a systematic assessment of both cognitive achievements and emotional and motivational changes. A brief overview of new developments. In response to these gaps, this study proposes an approach to assessing the effectiveness of STEM education using robotics. This article develops a special STEM competency scale that allows identifying these skills in children. In addition, the novelty lies in the combination of experimental design, quantitative analysis of learning outcomes, and questionnaires, which allows assessing both students' cognitive achievements and their emotional and motivational dynamics. In addition, the results of the study have the potential to be scaled to other educational institutions, which expands the practical value of the findings.

1.1. Objective

The aim of this study is to empirically assess the impact of using robotics as an important element of interactive learning on the development of STEM competencies of elementary school students. The fulfillment of this goal involves finding answers to the following research questions:

1. What level of STEM competencies do students have before introducing robotics into the educational process?
2. How does the level of STEM skills of students change after learning using robotics?
3. Is there a statistically significant difference between students who studied using robotics and those who studied traditionally?

The following hypotheses are proposed to confirm or refute them:

1. H1: The use of robotics in the educational process contributes to a significant improvement in STEM competencies of primary school students.
2. H2: Students in the experimental group will demonstrate higher results on the final test compared to the control group.
3. H0 (null hypothesis): The difference in the level of STEM competencies between the two groups is statistically insignificant.

2. Research method

2.1. Research design

The study is of the quasi-experimental-comparative type. This type involves comparing the results of two already formed groups (experimental and control) before and after the implementation of a certain pedagogical intervention. The choice of this particular design is due to the peculiarities of the educational environment, where it is impossible to conduct full randomization of participants. This approach allowed us to get as close as possible to the conditions of a "pure" experiment and preserve the ethical and organizational requirements of the school process. At the same time, conducting a comparative analysis influenced the assessment of the effectiveness of the introduction of robotics in STEM education for primary school students.

2.2. Sample and participants

The study used purposive sampling with the inclusion of 2 groups of participants in the experiment. Special inclusion criteria were developed for the inclusion of participants:

1. Students must be from the same educational institution and be studying in the 3rd grade;
2. Students must not have significant cognitive impairments or special educational needs that could affect the assimilation of educational material;
3. Providing informed consent of parents for the child's participation in the study;
4. Stable attendance of classes throughout the entire study period.

Accordingly, two groups of 3rd grade students at a comprehensive school were selected for the experiment:

The Experimental Group included 26 students;

The Control Group also included 26 students.

The total age range of participants: 8–10 years. All study participants and their parents were informed about the goals, conditions, and duration of the study. Informed consent from parents was obtained in writing before participation.

2. 3. Instruments and procedures

Various research instruments were used to measure changes in the level of STEM competencies. In particular, the use of an adapted STEM competency assessment scale played an important role. This scale included tasks on logic, spatial thinking, basic skills in science, technology, engineering and mathematics (See Appendix 1). The scale provides for the definition of 3 levels: high, medium and initial:

1. 16–20 points: high level of STEM competencies
2. 11–15 points: medium level
3. 0–10 points: initial level

A self-observation questionnaire for students, which indicated subjective perceptions of abilities and skills (See Appendix 2). This instrument used a Likert scale model from 1 to 5, where students had to rate their own attitude towards the learning process. This questionnaire also included the determination of the level of involvement in STEM:

1. 40–50: high level of involvement in STEM
2. 25–39: medium
3. <25: low

A significant role was played by the observation method. In particular, by the activity of education seekers and teamwork. The research procedure was staged. It consisted of pre-testing, in which both groups passed an initial test to determine the basic level of STEM competencies. After that, the training stage, which lasted 6-8 weeks. At this stage, the control group conducted classes according to the traditional STEM program, and the experimental group based on the use of STEM classes with the integration of robotics elements. The following aspects were considered:

1. Basic programming of robots.
2. Team project activity involving technologies;
3. Work with constructors.

After the end of the educational stage, a final test was conducted, which involved a re-evaluation of the level of STEM competencies.

The study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Institutional Review Board of the educational institutions where the implementation took place (comprehensive schools in two districts of Kyiv). Written informed consent was obtained from the parents or legal representatives of all participants before the study began. Confidentiality and anonymity of the participants were ensured at all stages of the study.

2.4. Data analysis

The data obtained from pre-testing, post-testing, questionnaires, and observations were processed using quantitative statistical analysis methods. Initially, after collecting all the data, the materials were additionally checked for completeness and integrity. The preliminary processing also included coding the responses using numerical values. This is evident in the use of the Likert scale. After that, the data was checked for completeness and validity. Next, they were processed using statistical analysis.

To assess the changes in the level of STEM competencies in the control and experimental groups, the mean values were compared using Student's t-test for independent samples (experimental vs. control group). The paired t-test method was also used to compare the results before and after the intervention within each group. After obtaining the results, they were compared with the data of other authors.

3. Results

The study of the impact of the use of robotics in the educational process on the development of STEM competencies in primary school students will help to identify opportunities for involving this innovative tool in the educational process. To measure the results, the author's scale of STEM competencies and a self-observation questionnaire were used. Before the start of the training, both groups were pre-tested using the STEM competencies scale. The data showed no statistically significant difference between the two groups analyzed, which allows us to consider them comparable in terms of initial indicators.

Table 1. Level of STEM competencies before the experiment

Group	N	Mean (M)	Standard Deviation (SD)	Min.	Max.
Control	26	11,5	2,1	8	16
Experimental	26	11,8	2,3	7	17

Source: Author's development

The results of the t-test (t(50)) = 0.48, p = 0.63. Thus, it was determined that the level of STEM competencies in the two selected groups was statistically the same for the study. After completing the educational program, retesting was conducted. After completing the six-week educational program, which included the inclusion of robotics elements in the experimental group, students in both groups were retested using the author's STEM competency scale. This test involved identifying the dynamics of changes in the level of relevant skills and knowledge. It also made it possible to verify the effectiveness of the use of robotics technologies in primary school. In particular, the analysis of the obtained indicators showed an increase in the level of STEM competencies in the experimental group. These indicators contrasted markedly with minimal changes in the control group. In particular, the data indicated that the average score of students who worked with robotics elements increased by 4.1 points (from 11.8 to 15.9), which is statistically significant. At the same time, there is only a minimal increase in the indicators in the control group (see Table 2).

Table 2. Dynamics of STEM competencies (before / after)

Group	Period	M	SD	t	p
Control	Before Expr.	11,5	2,1	1,62	0,11
	After Expr.	12,1	2,0		
Experimental	Before Expr.	11,8	2,3	6,74	<0,001
	After Expr.	15,9	1,8		

Source: Author's development

As can be seen in Table 2, the control group, which studied in a traditional STEM program without the use of robotics, gained only 0.6 points (from 11.5 to 12.1). This insignificant change was not statistically significant ($p = 0.11$). These results demonstrate stability and low variability of STEM competencies. At the same time, the participants of the experimental group who worked with robotics (LEGO construction, basic programming, team project work) showed a significant improvement in the level of STEM competencies - by 4.1 points (from 11.8 to 15.9). These results were statistically significant with an extremely high level of confidence ($t = 6.74$; $p < 0.001$). Such an increase showed a significant substantive pedagogical improvement, as it covers not only knowledge of natural sciences, mathematics and technology, but also the development of algorithmic thinking and the practical use of the acquired knowledge in the form of building models and solving real-world problems. The average value after the tests (15.9 points) also shows a high level of achievement for most applicants.

Based on the observation of students' behavior and activity, attention was drawn to the level of interest and activity in group tasks. In the experimental group, the most interesting elements of robotics for students were programming robot movements (based on LEGO WeDo / Spike Essential). In particular, the students actively and with interest set the robots' routes, changed their speed and direction, and observed the results. In general, the children showed enthusiasm. Designing models, i.e., building moving mechanisms, was also important [21]. The applicants were impressed by the opportunity to combine creativity with technology, in particular, to produce a design and form models from parts. Group work on the projects allowed us to record an increase in the level of communication with the students. In particular, many students actively shared ideas and talked about their own thoughts. Figure 1 shows the average values of STEM competencies in 2 groups of applicants.

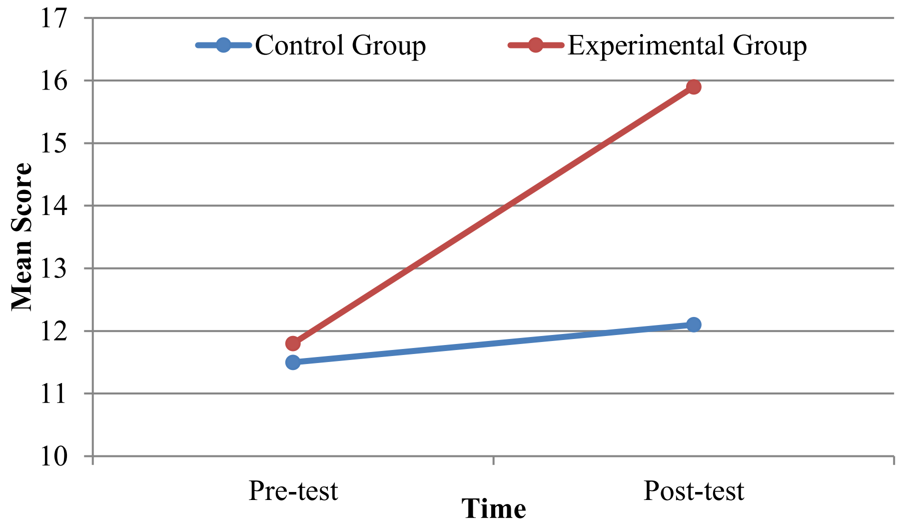

Figure 1. Dynamics of average values of STEM competencies

As shown in Figure 1, the experimental group showed significant changes in the level of STEM competencies. However, in the control group, the level of growth was insignificant. After processing the post-test data, the results of the two groups revealed a statistically significant difference. It is also more noticeable in the experimental group. This demonstrates the overall effectiveness of teaching with the use of robotics in the modern learning environment of primary school education. Table 3 shows the results of the students after the experiment. In particular, it shows that in the control group the average value of indicators is 12.1 out of 20. At the same time, in the experimental group - 15.9 out of 20 (see Table 3).

Table 3. Comparison of results after the experiment

Group	M	SD	t	p
Control	12,1	2,0		
Experimental	15,9	1,8	6,45	<0,001

Source: Author's development

In addition to the tests conducted, students also filled out a questionnaire based on their observation. It allowed us to determine the attitude of students to studying in STEM programs. In particular, in the control group, the average score of the questionnaires was 30.4. After training, it was 31.2, that is, only a slight improvement was obtained. At the same time, in the experimental group, the average score in the first test was 30.1, and after training - 39.8. Thus, there is a noticeable increase in subjective involvement, motivation and confidence in students in the experimental group (See Table 4).

Table 4. Average scores on the self-observation questionnaire (before / after)

Group	Period	M	SD	t	p
Control	Before Expr.	30,4	4,6	1,21	0,23
	After Expr.	31,2	4,2		
Experimental	Before Expr.	30,1	5,1	7,21	<0,001
	After Expr.	39,8	3,9		

Source: Author's development

These data indicate a significant increase in subjective engagement, motivation, and confidence in the students of the experimental group. The greatest improvement was observed in items related to teamwork, desire to experiment, and interest in programming.

The study also conducted a correlation analysis of the test results and self-observation questionnaires in order to establish the relationship between the objective level of STEM competencies and students' self-esteem. Thus, it was obtained that in the experimental group the correlation coefficient was $r = 0.64$ ($p < 0.01$). This indicator indicated a noticeably strong positive relationship. In general, this showed an increase in the general level of knowledge of students and their practical skills. At the same time, this increase was accompanied by the growth of students' confidence in their own abilities and the desire to solve non-typical tasks.

4. Discussion

Given the main research problem, namely, finding out the role of using robotics elements in primary school, the study revealed significant efficiency of using these technologies in the primary school system. The experiment between the two groups (control and experimental) not only determined the importance of using these technologies but also showed that students who studied with the use of robotics demonstrated significant activity and interest in learning.

The first research question concerned determining the level of students' STEM competencies before introducing robotics into the educational process. Accordingly, it was found that students from both groups had a similar level, so the results showed no statistically significant difference between the two groups analyzed. In general, similar results have been recorded in studies where students had the same level of performance before the intervention [22]. This allows us to confirm the representativeness of the selected sample, which is consistent with international data [23].

The next research question was to determine changes in the level of STEM competencies after robotics training. Accordingly, the results showed a significant improvement in the experimental group. In particular, as shown in the main part of the paper, the average score increased from 11.8 to 15.9, which is statistically significant ($t = 6.74$; $p < 0.001$). In the control group, the increase was insignificant (from 11.5 to 12.1; $p = 0.11$). Such results are also partially consistent with studies that show the importance of introducing robotics elements into the educational process [24]. In particular, studies have shown that robotics in STEM education allows students to experiment with physical phenomena, use various technologies in practice, create engineering solutions, and solve applied problems [25]. In addition, the current scientific literature shows that robotics affects the development of critical and logical thinking, as robot programming requires building algorithms, predicting outcomes, analyzing errors and correcting actions, and establishing cause and effect relationships [26]. At the same time, as proven in other works, robotics classes are usually held in a team format, which affects the development of children's cooperation skills [27], [28]. Such work helps to develop the ability to listen to others and share ideas [29]. The findings are also generally consistent with the meta-analysis of other researchers who have found that the use of educational robotics has a moderate positive impact on students' learning outcomes and attitudes toward STEM subjects [29]. In other studies, the effect was also pronounced when combining robotics with project-based learning and systematic teacher support [30], [31].

The proposed results noted a significant difference between students who studied using robotics and those who studied traditionally. In particular, in addition to the tests conducted, a questionnaire was conducted, which was based on the observation and self-reflection of students. In the control group, the average score of the questionnaires was 30.4, and after training - 31.2. At the same time, in the experimental group, the average score in the first test was 30.1, and after training - 39.8. The correlation analysis conducted demonstrated a noticeable positive relationship. This made it possible to note an increase in the general level of knowledge of students and their practical skills, and the increase was accompanied by an increase in students' self-confidence and a desire to solve atypical tasks. The results obtained correspond to the conclusions of other scientists who noted the existence of a positive relationship with the introduction of robotics and the development of STEM education in general [32], [33]. At the same time, some studies have highlighted such results in secondary school and university settings [34]. Similar trends have also been repeatedly noted in the primary school grades [35]. Although there have been opposing views among researchers about the effectiveness of robotics [36], [37]. Skepticism was primarily based on the belief that children at an early age do not perceive information critically enough and their digital skills are at an elementary level [38], [39]. This observation is worth noting - it points to the importance of pedagogical support when teaching robotics at an early stage [40]. Moreover, observation highlights the critical importance of pedagogical support in the early stages of robotics education [41]. The papers suggest that professional pedagogical support ensures that teaching methods are appropriately adapted to the developmental level of students [42], [43]. Furthermore, according to research, appropriate pedagogical guidance can bridge the gap between the novelty of robotics and the cognitive abilities of young students [44], [45]. The papers also suggest that professional pedagogy supports the ability to meaningfully engage learners in the content of education and develop the necessary skills at an early age [46], [47]. Therefore, it is important to provide appropriate pedagogical support that overcomes the difficulties associated with the level of development of children. This will allow for the effective integration of new technologies into the educational process.

The methodology used in the study has certain limitations that need to be taken into account when interpreting the obtained materials. First of all, there are certain elements of subjectivity in the tests conducted, since their results depended not only on the general influence of the educational environment, but also on the personal level of knowledge and skills of the students, which could differ significantly from the very beginning. It is also worth noting that the self-observation questionnaires had certain subjective statements, which, however, could have had a certain impact on the overall results obtained. In addition, an important drawback is the small number of participants. Accordingly, these limitations open up new directions for research. In particular, in future studies it is planned to explore the possibilities of robotics with the involvement of a large sample of participants, including students, parents and teachers.

5.Conclusions

Therefore, the analysis of the impact of the use of robotics on the educational process and the development of STEM competencies in primary school students made it possible to identify individual elements of this innovative tool. As a result, it was determined that after completing the educational program, which included the inclusion of robotics elements in the experimental group, there was a significant increase in the level of STEM competencies in the experimental group. The obtained indicators contrasted markedly with minimal changes in the control group. In the control group, stability and weak variability of STEM competencies were revealed, while the participants of the experimental group who worked with the use of robotics showed a noticeable improvement in the level of STEM competencies. Based on the observation of the behavior and activity of students, it was established that in the experimental group, the most interesting elements of robotics for students were programming robot movements. In general, the children demonstrated enthusiasm, while the design of models, i.e., the construction of moving mechanisms, also became important. The students were impressed by the opportunity to combine creativity with technology, in particular, to produce a design and form models from parts.

It was also determined that the students in the control group noted a slight improvement in their skills. In the experimental group, the average score in the first test was 30.1, and after training - 39.8. Thus, there is a noticeable increase in subjective involvement, motivation and confidence in the students of the experimental group. In general, an increase in the general level of knowledge of the students and their practical skills was shown. At the same time, this increase was accompanied by an increase in the students' self-confidence and desire to solve atypical tasks.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

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