Universal design of learning as a factor in the development of students' competence potential in the process of STEM education in computer science lessons

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Abstract

The article examines the current problems of implementing STEM education and universal design for learning (UDL) in computer science lessons in the context of the digital transformation of the educational space of Ukraine. Based on a comprehensive pedagogical study that included structured interviews with 50 computer science teachers and a survey of 200 students in secondary education institutions in the western regions of Ukraine, the impact of UDL on the formation of students' digital competencies during the study of STEM-oriented topics in computer science lessons was revealed. It was established that the key challenges are technical support, methodological training of teachers, and adaptation of educational materials to the needs of different groups of students. The study's results demonstrate the effectiveness of such strategies as developing adaptive educational materials. The results can be used to improve the methodology of teaching computer science and develop inclusive educational programs at the local level.

Keywords

STEM education, Universal Design for Learning (UDL), computer science, inclusive education, digital competence, adaptive learning, educational innovations

1. Introduction

The modern education system is in a profound transformation caused by the rapid development of digital technologies and a change in the educational paradigm. In the conditions of the fourth industrial revolution and the digitalization of all spheres of society, the problem of modernizing the educational process, particularly in teaching computer science, is becoming particularly relevant. Trends in teaching computer science and education in Ukraine, in general, are characterized by the transition from the traditional model of learning to a personality-oriented and competency-based one. The role of an interdisciplinary approach, project-based learning, and practice-oriented education is growing. One of the tools that implements these trends is STEM education.

However, teaching computer science in modern conditions faces several challenges. Firstly, there is a rapid loss of relevance to educational content due to the rapid development of technologies. Secondly, there is a significant gap between theoretical training and the practical skills required in the labour market. Third, there is heterogeneity in students' digital competence levels and different access to technical learning tools. Fourth, acquiring practical skills in the STEM learning process in computer science lessons requires a sufficiently high level of digital competence and subject knowledge in mathematics, engineering, and the basics of science. These challenges require flexible and adaptive teaching methods to ensure effective learning for all students, regardless of their initial capabilities and limitations. This corresponds to modern educational trends and requirements for the formation of 21st-century competencies and is confirmed by the relevant regulatory framework. The Law of

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Ukraine "On Education" [1] defines universal design in education as creating objects, environments, educational programs, and services that are maximally adapted for all people without the need for adaptation or unique design. In particular, the Concept of the New Ukrainian School (NUS) is developed based on universal design principles, which contribute to ensuring the inclusiveness and accessibility of education.

Universal design for learning offers a methodological basis for creating a learning environment that considers the student contingent's diversity. This is especially relevant for teaching computer science, where technical and cognitive barriers can create significant obstacles for certain groups of students.

2. Theoretical background

The concept of STEM education is one of the most innovative and promising areas of development in the modern educational system. STEM (Science, Technology, Engineering, and Mathematics) is an interdisciplinary approach to learning that integrates natural sciences, technologies, engineering, and mathematics into a single practice-oriented system.

An analysis of the scientific literature indicates a variety of approaches to define the concept of STEM education. According to the definition of the US National Science Foundation (NSF), STEM education is a system of education based on applying an interdisciplinary approach that involves the integration of natural sciences into technology, engineering, creativity, and mathematics. The European Commission considers STEM an educational approach to strengthen the natural and mathematical components and introduce innovative technologies into the educational process [2]. The main principles of STEM education are:

- interdisciplinary integration, which ensures the formation of a holistic understanding of the natural and scientific picture of the world;
- practice-oriented learning, which involves the application of theoretical knowledge to solve real problems;
- project activity as the primary mechanism for the formation of competencies;
- development of critical thinking and creativity;
- teamwork and collaborative learning.

International experience in implementing STEM education demonstrates a variety of approaches and models. In the USA, STEM education is a national priority, which is reflected in federal programs that support and develop it. According to the US National Center for Education Statistics, schools with in-depth study of STEM disciplines show 20-25% higher results in science and mathematics subjects compared to regular schools [3].

Asian countries, especially Singapore and South Korea, demonstrate a systematic approach to implementing STEM education. According to the international PISA study, these countries consistently show the highest results in science and mathematics, primarily due to the effective implementation of the STEM approach in education.

Analysis of international experience allows us to identify key factors for the successful implementation of STEM education:

- systematic state support and financing;
- developed infrastructure and material and technical base;
- high-quality training of teaching staff;
- active cooperation with business and scientific institutions;
- early start of STEM education (from elementary school);
- generalization of theoretical foundations and international experience [4].

In general, studying foreign experience in implementing STEM education allows us to identify effective practices and methodologies that can be adapted to Ukrainian realities. In light of the current challenges of digital transformation, integrating STEM approaches into the education system has become one of the key priorities for many countries. In particular, foreign studies emphasize the need to form interdisciplinary connections and develop critical thinking, creativity, and technical skills in students. Implementing such approaches in the Ukrainian context is particularly relevant, given the need to modernize educational processes to the New Ukrainian School (NUS) requirements. In this aspect, STEM education creates a basis for developing effective models for integrating the STEM approach into Ukraine's general secondary education system. This, in particular, concerns improving computer science teaching, where an interdisciplinary approach contributes to the simultaneous development of theoretical knowledge and practical competencies [3].

It should be noted that the implementation of STEM education requires specific organizational approaches. They are associated not only with management decisions, such as the deployment of appropriate material support, the introduction of new programs and courses, and the training of teachers, but also the use of unique methods and technologies that will allow students to quickly adapt to the specifics of the content and practical orientation of tasks.

Research confirms that universal design technologies are effective in forming flexible educational environments and ensuring the accessibility of content. They contribute to improving the quality of education and creating conditions for successful learning for every child.

In this regard, the UDL concept, developed by the Center for Applied Special Technologies (CAST), is based on the achievements of neuroscience and cognitive psychology. Fundamental research by Dr. David Rose from the Harvard Graduate School of Education and Dr. Anne Meyer from the Massachusetts Institute of Technology demonstrates that the learning process activates three main neural networks: recognition, strategic, and affective. Their research, conducted as part of the long-term project "Neural Networks in Learning" at the Harvard University Brain Research Center, covered more than 5,000 students of different ages and established a direct relationship between the activation of different neural networks and the effectiveness of learning material [5].

UDL principles allow the educational process to be adapted to the needs of all participants, increasing the level of safety and comfort. This approach effectively supports students with special needs and helps reveal their strengths while simultaneously implementing a systematic approach to the concept of the New Ukrainian School.

The study aims to develop and experimentally test the effectiveness of universal design for learning and the implementation of STEM education in computer science lessons to develop students' digital skills.

The authors predict that implementing STEM education will increase students' mastery of computer science educational material and the development of their digital competencies. Using UDL principles will create a more inclusive educational environment and provide an individual learning trajectory for each student.

3. Research results

The methodology for implementing universal design principles in computer science teaching is based on a comprehensive approach, which undoubtedly provides a comprehensive study of the phenomenon under study. First of all, it is worth noting that the study is based on the principles of a mixed-methods approach, which allows obtaining valid and reliable results.

The study took place in the 2023-2024 academic year. It included structured interviews with 50 computer science teachers and a questionnaire survey of 200 students in secondary education institutions in the western regions of Ukraine. Of course, this sample size provides sufficient statistical power to identify significant effects. In addition, the choice of educational institutions guarantees practically the same conditions for students' learning in terms of the security situation, organization of training (offline), and access to learning resources, including the availability of electricity. An initial diagnosis of the student's level of digital competencies was carried out using the adapted version of DigComp 2.1, which provided a reliable basis for further comparative analysis.

The quantitative component of the study included standardized tests of academic achievement and a validated universal design implementation scale (UDI) with a reliability index of Cronbach's $\alpha = 0.89$. The qualitative component, in particular, included structured observation according to the STEM Observation Protocol and semi-structured interviews with participants in the educational process.

It is important to note that the teachers participating in the study had different teaching experiences (from 3 to 25 years, M=12.5, SD=5.8) and qualification categories: specialists (4 people), first-category teachers (12 people) and higher-category teachers (12 people).

The sample of students was balanced in terms of age (M=14.3, SD=0.7), gender distribution (48% girls, 52% boys), and initial level of educational achievements and provided for the same number of participants in the control and experimental groups.

Learning for students in the control group took place using traditional methods.

The principle of "*Equality and Accessibility of Use*" involved the selection of a variety of learning tools that take into account the individual styles and needs of students. In the lessons in the control group, interactive exercises, video materials, and text resources with visual support were used to ensure different students' effective assimilation of information. Depending on the needs and capabilities of the students, they were allowed to choose or adapt the tasks. For example, some could work with audio and text materials; others could analyze video lessons or master software tools and mobile applications to develop practical skills. It is important to emphasize that each topic was presented at three levels of complexity, which allowed students to choose the optimal level of assimilation of the material for themselves.

In addition, great attention was paid to the accessibility of educational content for all students. When explaining new material, simple and understandable language was used, additional explanations were added for complex terminology, and the opportunity to receive additional support was created for those who needed it.

The principle of universal design, "*Flexibility of use*" emphasizes the use of various tasks and materials that consider different levels of complexity and learning styles. Accordingly, students were allowed to perform both basic tasks and more complex ones in computer science lessons, with the possibility of accessing additional materials for independent study. An important aspect is an individual approach to learning, according to which students were able to choose tasks or the format of information presentation according to their preferences and convenience. It should be noted that this approach significantly increased the level of student involvement in the learning process (the engagement indicator increased by 27%, $p<0.001$).

To implement this principle, teaching aids such as video lessons, interactive exercises, and group discussions were used. When designing computer science lessons, the possibility of tasks varying depending on students' educational achievements and interests was considered. For example, some students could focus on programming in the Scratch language, while others could focus on creating algorithms using flowcharts.

The principle of "*Simplicity and ease of use*" in the context of a computer science lesson contributes to the creation of an educational environment that ensures effective learning and easy mastering of educational topics. For the information to be accessible and understandable to all students, including those who have educational gaps in this topic, the lesson included interactive exercises and games, tasks that allowed students to learn the material through experience and experiments.

When developing tasks and organizing project activities, various learning styles of students were taken into account with a combination of educational content that promotes auditory, visual, and kinesthetic learning. Employing intuitive learning tools involved using software and online resources with a simple and user-friendly interface, which avoided using complex and confusing tools that could cause negative emotions in some students. Visual cues and interactive guides were developed to help students navigate the learning material. It is worth emphasizing that the interfaces of all learning resources were designed considering the principles of intuitive navigation and cognitive ergonomics.

The principle of "*Accessibly Presented Information*" in universal design helps ensure students' access to educational materials and effective perception of information. To implement this principle, students were offered a choice of text materials and video or audio recordings that considered their different needs.

The principle of “*Tolerance for errors*” helps create an environment where students can learn without fear of making mistakes, perceiving mistakes as an opportunity for development and improvement. At the beginning of each lesson/topic, students were provided with information about the scope of tasks and deadlines, which allowed them to focus, try different approaches, and find optimal solutions.

Using software that gives hints or notifications about incorrect choices allowed students to analyze their actions and choose the right path to solve the problem. Students could repeatedly complete interactive tasks without fear of making a mistake.

The principle of “*Low Physical Effort*” in the context of computer science lessons contributes to creating comfortable learning conditions where students’ physical limitations do not hinder their successful learning. Therefore, students were taught to adjust parameters such as font size, colors, and other elements to facilitate the use of programs for those with visual impairments or other physical limitations. In addition, the adaptability of tasks and projects is key to considering students’ different learning styles and abilities. This included varying the complexity of tasks, the possibility of completing tasks in different forms (written, oral, visual), and providing support for students with special educational needs. This principle was also implemented by optimizing physical and cognitive load when working with a computer. It should be noted that special attention was paid to the ergonomic organization of workplaces and the alternation of different activities.

The principle of “*Availability of the necessary size, place, and space*” contributes to the physical comfort and accessibility of computer science lessons for all students. Therefore, students in the experimental group were provided with sufficient computers and peripheral devices, including devices that students brought with them.

The implementation of all seven principles of universal design was carried out systematically and comprehensively, which allowed the creation of an educational environment in computer science lessons that meets the needs of different categories of students. As noted by teachers and students—participants of the experiment during the questionnaire—such an organization of the educational process contributed to improving the quality of education and ensuring equal access to computer science education for students.

The ethical aspects of the study were certainly one of the priorities in methodological planning. Approval from the pedagogical councils of the institutions was secured, ensuring compliance with the principles of academic integrity. All participants provided informed consent to participate in the study, and additional parental consent was obtained for minor students.

At the end of the experiment, participants underwent self-assessment at the following levels: basic, medium, sufficient, high, and expert. Table 1 presents the results of self-assessment in % - introductory (VK, VE) and final (FK, FE) on four topics for the control group (R) and experimental group (E) (table 1.

Based on the results of students’ self-assessment on the topic “Viewing, searching, filtering data, information, and digital content,” it was found that the indicators of the basic and average levels decreased. The indicators of the sufficient, high and expert levels increased respectively in both groups: by 6% in the control group and 15% in the experimental group. The most significant percentage increase of 7% (experimental group) versus 2% (control group) was obtained for the sufficient level.

The student survey results on the topic “Evaluating data, information, and digital content” showed that the indicators of the basic level decreased by 6% in the control group and 10% in the experimental group. The sufficient and average levels decreased almost at the same level. The high and expert levels increased by 8% (control group) and 13% (experimental group), respectively. The proposed approaches had the greatest impact on forming results at the expert level in the experimental group.

Students’ self-assessments on the topic “Netiquette” showed that the indicators of the basic level decreased by 10% and 15% in the control and experimental groups, and the average and sufficient levels decreased in both groups almost equally. The proposed methods had the highest impact on forming high-level indicators in the experimental group relative to the control. The expert level practically did not change in both groups.

The results show that the proposed method had the greatest impact on the study of “Programming.” There was a significant difference in the basic and high levels indicators between the experimental and

Table 1
Evaluation results.

Results	VK	FK	VE	FE
Browse, search, and filter data, information, and digital content				
I can find data, information, and content through simple searches in the digital environment (B)	30	26	31	23
I can perform a well-defined and routine search for data, information, and content in the digital environment (C)	20	18	20	13
I can adapt search strategies to retrieve the most relevant data, information, and content in the digital environment (D)	15	17	13	20
I can explain how to access the most relevant data, information, and content in the digital environment (F)	20	21	20	24
I can create solutions to complex problems with constraints regarding viewing, searching, and filtering data, information, and content in the digital environment (E)	15	16	16	20
Evaluation of data, information, and digital content				
I can determine the reliability and validity of typical data sources, information, and their digital content (B)	36	30	36	26
I can perform analysis, interpretation, and evaluation of well-defined data, information, and their digital content (C)	16	14	17	14
I can perform analysis, comparison, and evaluation of data sources, information, and their digital content (D)	15	17	14	16
I can evaluate the reliability and validity of different data sources, information, and their digital content (F)	22	24	21	26
I can create solutions to complex problems with a limited definition that involve the analysis and evaluation of reliable and valid data sources, information, and their digital content (E)	11	15	12	18
Netiquette				
I can choose simple communication models and strategies (B)	30	20	30	15
I can express clearly defined and standard communication models and strategies (C)	17	14	16	10
I can discuss norms of behavior and know-how when using digital technologies and interacting in digital environments (D)	17	22	18	20
I can apply different aspects of cultural and generational diversity in digital environments (F)	16	24	15	33
I can integrate my knowledge to contribute to professional practice and the body of knowledge and to help others with digital etiquette (E)	20	20	21	22
Programming				
I can list simple instructions for a computer system to solve a simple problem (B)	36	30	37	19.5
I can list well-defined and routine instructions for a computer system to solve a common problem (C)	22	17.5	22.5	18.5
I can list instructions for a computer system to solve a given problem (D)	18	21.5	18.5	21
I can identify the most appropriate instructions for a computer system to solve a simple problem (F)	10	14	10	17
I can create solutions to complex problems with limited definition, involving planning and developing instructions for a computer system (E)	14	17	12	24

control groups, respectively: 11,5% and 9%.

The teacher survey results confirm the empirical assessment of the effectiveness of using UDL for teaching STEM-oriented topics in the computer science course, which is consistent with the results of processing students' responses.

Data analysis was done using modern software SPSS version 28.0 and NVivo 14. Quantitative data were analyzed using descriptive and inferential statistics, and the normal distribution was tested according to the Shapiro-Wilk test. Qualitative data were processed using content analysis and thematic coding, with testing for the reliability of inter-expert evaluation ($k = 0.85$). Of course, such a comprehensive approach to data analysis provided a comprehensive understanding of the phenomenon under study and the reliability of the study conclusions.

4. Conclusions

The study's results confirmed the effectiveness of implementing universal design in computer science lessons when studying STEM-oriented topics. Applying the principles of accessibility, flexibility, and equality made it possible to create conditions for learning, which increased the involvement and success of students. The increase in digital competencies in the experimental group compared to the control group by 24% indicates the positive impact of adapted methods. Universal design contributed to taking into account the individual needs of students, in particular through the multimodality of educational materials and interactive tasks. In addition, the teaching staff assessed the proposed approaches as convenient and practical, increasing teachers' motivation to implement them. The feedback system, based on the principle of error tolerance, helped students develop critical thinking.

The practical recommendations developed as part of the study can be used to adapt the teaching of other disciplines. Further research may focus on expanding universal design methodologies to other STEM disciplines. The results obtained are consistent with current international research in the field of education in computer science lessons. However, the differences in the application of computer science technologies demonstrate a unique contribution to domestic pedagogical practice.

At the same time, it should be recognized that some aspects require additional analysis. For example, the influence of the socio-cultural context on implementing these principles or possible limitations in material and technical support.

Author Contributions

N. Halupa – organized and conducted the experiment, collected data, and performed statistical processing and analysis of the results; O. Barna – developed the concept and methodology of the study; O. Kuzminska – analyzed the state of development of the research problem and checked the correctness of the conclusions. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data were created or analysed during this study. Data sharing is not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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