ПЕДАГОГІЧНА АКАДЕМІЯ:
НАУКОВІ ЗАПИСКИ

Теорія та методика навчання

УДК 37.02:004.93
DOI https://doi.org/10.5281/zenodo.19645296

Use of computer visualization tools in education: generalization of existing practices

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ПЕДАГОГІЧНА АКАДЕМІЯ:
НАУКОВІ ЗАПИСКИ

Прийнято: 11.03.2026 | Опубліковано: 30.03.2026

Abstract: Problem statement. *Modern education is undergoing significant transformations associated with integrating digital technologies, among which computer visualization tools occupy a special place. They play a key role in improving the quality of learning, contributing to a better assimilation of complex concepts through the visual presentation of information. However, despite the widespread use of these technologies, there is a dearth of generalized data on their effectiveness, optimal use cases, and potential limitations. The purpose of this article is to review and summarize the existing practices of using computer visualization tools in education.* ***Materials and methods.*** *We used the following methods of scientific cognition: analysis and synthesis to analyze individual aspects of computer visualization, comparative study to compare the effectiveness of different visualization tools in education, classification to group computer visualization tools, systematic review to identify already existing results of the efficacy of visualization, descriptive analysis to record existing practices.* ***Results.*** *The article defines the directions for implementing computer visualization, particularly scientific, software, and information visualization. Practices for using program visualization tools, mathematical and scientific visualization tools, data visualization tools, and augmented and virtual reality have been identified. The generalization of scientific content was evidenced by visualization in various subject areas: STEM education, computer modeling, and programming education. Some studies confirm the effectiveness of visualization tools in education, particularly the positive impact on learning outcomes, interest and motivation, cognitive processing, and understanding of the material.* ***Conclusions.*** *Positive impacts highlight the potential of visualization tools for STEM education. The development and implementation of new disciplines focused on visualization are being actualized. The development of visualization tools*

 ISSN: 2786-9458

that adapt to individual needs and learning styles is a promising area of research on personalization and adaptive approaches in education.

Keywords: *computer visualization; education; digital tools; IT; visualization tools; education.*

Використання засобів комп'ютерної візуалізації в освіті: узагальнення наявних практик

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Анотація:* Постановка проблеми.** *Сучасна освіта переживає значні трансформації, пов’язані з інтеграцією цифрових технологій, серед яких особливе місце займають інструменти комп’ютерної візуалізації. Вони відіграють ключову роль у підвищенні якості навчання, сприяючи кращому засвоєнню складних понять через наочне подання інформації. Проте, незважаючи на широке застосування цих технологій, існує дефіцит узагальнених даних щодо їхньої реальної ефективності, оптимальних сфер використання та потенційних обмежень. Метою цієї статті є огляд і узагальнення наявних практик використання засобів комп'ютерної візуалізації в освіті.* ***Матеріали і методи. *Ми використали такі методи наукового пізнання: аналіз і синтез для розбору окремих аспектів комп’ютерної візуалізації, порівняльний аналіз для зіставлення ефективності різних інструментів візуалізації в освіті, класифікація для групування інструментів комп’ютерної візуалізації, систематичний огляд для виявлення вже існуючих результатів щодо ефективності візуалізації, описовий аналіз для фіксації існуючих практик.* ***Результати.*** *У статті визначено напрями реалізації комп'ютерної візуалізації, зокрема наукової, програмної та інформаційної візуалізації. Виявлено практики використання засоби візуалізації програм, інструментів математичної та наукової візуалізації, інструментів візуалізації даних, доповненої та віртуальна реальності. Узагальнення наукового контенту засвідчило використання візуалізації за різними предметними напрямами: STEM-освіта та комп'ютерне моделювання, освіта з програмування. Окремі дослідження підтверджують ефективність інструментів візуалізації в освіті, зокрема, позитивний вплив на результати навчання, зацікавленість та мотивацію, когнітивну обробку та розуміння матеріалу.* ***Висновки.*** *Позитивні впливи підкреслюють потенціал інструментів візуалізації для STEM-освіти. Актуалізується розроблення й упровадження нових дисциплін, орієнтованих на візуалізацію. Розробка засобів візуалізації, які адаптуються до індивідуальних потреб та стилів навчання, є*

перспективним напрямком досліджень, присвячених персоналізації та адаптивним підходам в освіті.

Ключові слова: *комп'ютерна візуалізація; освіта; цифрові засоби; IT; засоби візуалізації; освіта.*

Problem Statement. Computer visualization tools have revolutionized educational approaches in many disciplines, changing how complex concepts are presented and understood. Graphic information can be interpreted faster and more accurately than information transmitted in written or oral language. Visualization is used to clarify or convey ideas, overcome language barriers, process information quickly, and change the storyboard process [9]. The evolution and application of these tools is a significant shift in pedagogical methodologies, especially in STEM (science, technology, engineering, and mathematics) education. Studies have shown that integrating computer modeling into teaching methods is a promising way to develop scientific expertise and holistic understanding among students [11].

The importance of visualization in education stems from its ability to make abstract concepts tangible. Computer simulations make it easier to visualize abstract phenomena, such as molecular changes and planetary motion, that are otherwise difficult to observe in traditional class settings [16]. This aspect is especially valuable in disciplines that deal with complex, dynamic, or microscopic phenomena that cannot be directly observed in traditional classroom settings. Simulation tools designed for research can provide deep insights into physical processes, interactive visualizations of phenomena that might otherwise be invisible, and the ability to investigate in silico as it would be studied in the laboratory, but in a much shorter timeframe. Expanding access to significant computing power and efficient simulation code has made powerful computational modeling tools available to engineering researchers, educators, and students around the world, making processes at the atomic level visible [4].

Analysis of current research in the context of the historical evolution of visualization technologies in education. The use of visualization tools in education has evolved significantly over time. The historical context of introducing electronic visualization tools in education can be traced back to the first projectors in the 1930s to modern computer imaging technologies such as 2D and 3D visualization, stereoscopic 3D, virtual reality, and augmented reality [30]. These technological advances have changed how teachers present information and how students interact with learning materials.

In the early stages, visualization in education was mainly limited to static representations, such as text illustrations, films, and projections from above. In traditional education, visualization approaches included text illustrations, films, overhead, whiteboard sketches, and physical prototypes. The two main limitations of these imaging approaches were interactivity and/or accessibility [9]. These traditional methods, although valuable, lacked the dynamic and interactive qualities offered by modern computer visualization tools.

The advent of personal computers marked a significant turning point for visualization in education. A quiet revolution took place in the scientific laboratories of physics. Today, the personal computer is ubiquitous. It controls the experiment using clock motors, piezo micro drives, etc., controls all parameters, and collects experimental data using intelligent sensors. In particular, modern computer scanning and visualization methods open the possibility of creating genuinely new types of experiments. A computer allows you to store and process data on the one hand and conduct simulation and simulation on the other [15]. This revolution in research labs has gradually made its way into the educational environment, changing how students learn and interact with complex concepts.

In the 1990s and early 2000s, specialized software for visualizing education appeared. Among the groundbreaking tools was QuickTime VR, which allowed interactive visualization of anatomical structures. While its core features may be most

ISSN: 2786-9458

commonly used to produce and deliver typical video applications (e.g., lecture videos), QuickTime VR's additional virtual reality features can be used to create photorealistic, interactive "nonlinear films" of anatomical structures ranging in size from microscopic to gross anatomical [17]. Program visualization tools were also developed during this period to help students understand computer programming concepts. Recently, a dynamic visualization tool called ViLLE was created. It is language-independent and aims to provide a more abstract view of programming [10]. In recent years, there has been a significant shift towards web-based and mobile visualization tools.

Recent scholarly discourse (2020-2025) emphasizes the shift from simple static illustrations to immersive, interactive, and data-driven visualization environments. The analysis of current research reveals several dominant trends:

- *Virtual and Augmented Reality in CS Education.* A systematic review of studies from the last decade highlights that VR has become a cornerstone for improving computer science education, providing immersive environments that enhance student engagement. Mobile AR systems are also recognized as promising tools, especially in resource-constrained or distance learning scenarios, by overlaying interactive data on real-world elements [34].
- *Dynamic Program Visualization (PV).* Current research on tools like C Tutor and PythonTutor demonstrates their effectiveness in helping students understand complex programming concepts and execution flows. Studies in Portugal and Serbia have specifically linked the use of such tools to improved student progress and confidence in introductory programming courses [35].
- *STEM and Mathematical Modeling.* The synthesis of modeling, visualization, and programming within platforms like GeoGebra remains a highly effective approach. Recent findings indicate that GeoGebra significantly improves the skills of students in advanced courses, such as calculus and linear algebra, by making abstract concepts tangible [22].

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- *Computer Simulations vs. Traditional Experiments.* Comparative studies published in 2022 suggest that while computer simulations may impose a higher cognitive load, they often lead to higher academic success than physical experiments, particularly when teaching complex scientific topics [23].
- *Data Visualization and Literacy.* With the rise of big data, tools like Tableau are being integrated into curricula to enhance students' analytical and visual skills, fostering essential digital competencies for the modern workforce [26].
- *Pedagogical Challenges and Barriers.* Recent literature also addresses the "implementation gap." Despite the proven benefits of simulations and PV tools, many educators face obstacles related to the complexity of tool development and the lack of theoretically sound frameworks for their integration into lecture halls [31].
- *Accessibility and Personalization.* A significant trend in 2023–2025 research is the focus on handheld AR solutions for people with disabilities. There is a growing demand for adaptive visualization tools that can be personalized to individual learning styles and needs [29].
- *Digital Tools in Specialized Disciplines.* In medical education, recent practices involve the use of 3D multimedia complexes and virtual atlases to simulate living conditions and anatomical structures, which is crucial for deep biological understanding [33].
- *STEM-Project Based Learning.* Recent studies (2022) emphasize that STEM projects serve as a vital means for training future teachers in modeling, combining theoretical knowledge with practical, visual-heavy applications [18].
- *Interactive Technologies.* The use of interactive boards and web-based platforms is being analyzed as a way to create a more collaborative and visually-rich educational environment, specifically for teaching coding and technical disciplines [27].

The article aims to review and generalize the existing practices of using computer visualization tools in education. We summarize the technical evolution of

ISSN: 2786-9458

these tools, describe their use in education, and consider formal assessments of their effectiveness for schooling.

The study is of theoretical importance and practical orientation since its conclusions can become the basis for improving curricula, developing new educational products, and forming recommendations for teachers. In the context of the constant updating of digital solutions and the growth of competition in education, such a generalization is significant for further progress in the industry.

Materials and methods. To achieve this goal, we used the following methods of scientific cognition: analysis and synthesis to analyze individual aspects of computer visualization (in particular, technologies and pedagogical approaches) with further generalization to identify common trends, advantages and disadvantages of different practices; comparative analysis to compare the effectiveness of various visualization tools in education (in particular, 3D modeling, AR/VR, interactive graphs); classification for grouping computer visualization tools by criteria (e.g., level of interactivity, subject areas); systematic review to identify pre-existing results on imaging performance; descriptive analysis to record existing practices, their technical characteristics and application in education; case study to provide specific examples of the use of visualization in educational institutions; Historical analysis to investigate the evolution of computer imaging technologies in education.

Results. Imaging tools in education can be classified according to their functionality, purpose, and scope. The article defines the directions for the implementation of computer visualization, particularly scientific, software, and information visualization. It has been established that all visual content can be divided into three subgroups: structured, artistic, and demonstration visual objects, which can be static or dynamic in a single plane or three-dimensional space [30].

Application visualization tools. Application visualization tools constitute a significant category, especially in computer science education. Program visualization is a field of research that studies ways to visually assist students in understanding

ISSN: 2786-9458

program behavior. Application visualization can be either dynamic or static. Dynamic program visualization tools visualize the execution of programs. They usually show how programs are executed by highlighting the parts of code being executed and visualizing changes in the states of variables [10]. Prominent examples of such tools are ViLLE, Python Tutor, and PROVIT-CI. Application Visualization (PV) is an educational tool often used to assist users in understanding the flow of an application. PV is quite effective in assisting learners in completing several programming subtasks. PV can help students to some extent in learning the complex topics of the introductory programming course [6]. These tools help visualize the execution of programs, making abstract programming concepts more concrete and understandable.

Mathematical and scientific visualization tools. These tools focus on making abstract mathematical and scientific concepts more accessible. GeoGebra is an interactive geometry, algebra, statistics, and computational learning program designed to teach and learn mathematics, science, and engineering. Its dynamic interface allows users to accurately and interactively visualize models and results. GeoGebra syntheses three key functions: modeling, visualization, and programming [24]. These tools allow students to interact with mathematical models and scientific simulations, deepening their understanding of complex phenomena [32].

Flow visualization tools are another essential subcategory in scientific visualization. To achieve the educational goal, the authors of the study [19] integrate several methods into FlowVisual, including tracing field lines, comparing them, identifying and classifying critical points, and surface visualization [19], thereby helping students to imagine and understand fluid dynamics and other complex physical phenomena.

Data visualization tools. Data visualization tools focus on presenting and interpreting datasets, which is becoming increasingly important in the era of big data. Various digital data visualization tools, such as Tableau, enhance students' analytical

ISSN: 2786-9458

and visual skills [13]. These tools help develop digital skills in analyzing and interpreting complex datasets.

Augmented and virtual reality. Augmented reality (AR) and virtual reality (VR) are the newest stages in visualizing education. Among these technologies, augmented reality (AR) is a promising approach, allowing computer-generated interactive data to be visualized on top of real-world elements, thereby improving understanding and intuition about educational content, often in mobile settings. A dual-interface system allows educators and students to develop and interact with AR content directly related to academic outcomes. The authors Nunes at al. [8] argue that the design of ARPocketLab, aimed at manual operationalization using a minimal set of physical resources, is especially relevant in conditions of shortage of training materials or in situations where distance learning becomes necessary. Such immersive technologies provide students with new ways to interact with educational content. A study [1] substantiated the role of virtual reality in computer science teaching over the past 10 years. Through bibliometrics and content analysis of articles related to the use of VR in education, the authors characterized the current points of research in VR that have appeared recently and are promising for improving computer science education [1]. The growing interest in VR for computer science education reflects the potential of immersive imaging technologies to enhance the learning experience.

The generalization of scientific content indicates using visualization in various subject areas.

STEM education and computer modeling. Computer visualization tools are widely used in STEM education, in particular for computer modeling. In the review publication [16], the authors explore the role of computer modeling in science education to synthesize its effectiveness in deepening students' understanding of complex scientific concepts. The study results demonstrate that computer modeling positively affects student engagement and motivation, leading to increased interest, participation, and critical thinking skills in science subjects. The effectiveness of

ISSN: 2786-9458

computer simulations in STEM education has been demonstrated in numerous studies, including [21]. The "Understanding" phase [11] emphasized how PhET simulations contributed to a more profound understanding as students made in-depth observations. The "Application" phase demonstrated the effective transformation of knowledge gained from simulation into practical scenarios, combining theoretical and real-world experience of physical processes. Students' use of high-order thinking skills at the stages of analysis, evaluation, and creativity has shown that modeling contributes to assimilating scientific concepts [11]. These results highlight the potential of visualization tools to improve content knowledge and higher-order thinking skills.

Education in programming. In programming education, visualization tools are essential in helping students understand abstract programming concepts [14]. The introduction of C Tutor, a well-known program visualization tool, into programming courses has shown students' progress (improved knowledge and confidence) and the feasibility and usefulness of C Tutor [2]. Research [3] demonstrated that multimedia technologies have been used to create an interactive environment for learning programming on JavaScript. Visualization concepts have been included to provide visual learning of variables, loops, control structures, functions, etc. (the user can understand programming concepts and execute codes using a code bar [3]).

Medical and anatomical education. Imaging tools have had a profound impact on medical and anatomical education. Visualization of anatomical structures has expanded students' understanding of complex biological systems. Currently, there are a large number of computer programs and applications that allow students to deepen their knowledge of the structure of the human body. Such imaging systems include the 3D Atlas of Human Anatomy, 3D Organon VR Anatomy, an interactive anatomical atlas that demonstrates the operation of various human body systems [28]. The methodological functions of these teaching tools are closely related to the specifics of teaching human anatomy in medical schools or universities and to the real simulation of living conditions in the educational process.

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Some studies confirm the effectiveness of visualization tools in education.

Impact on learning outcomes. Studies consistently demonstrate the positive effects of computer visualization tools on learning outcomes. Many studies have shown the positive impact of GeoGebra on the efficiency and effectiveness of learning and teaching topics related to science, technology, engineering, and mathematics. Studies [12; 24] have shown how GeoGebra improves the skills of schoolchildren and students in advanced mathematics courses such as calculus, mathematical statistics, linear algebra, linear programming, computer-aided design, computer-aided geometric design, analytical, and projective geometry. A comparative study [7] gave an idea of the relative effectiveness of different imaging approaches. Regardless of the place of study, the results showed higher academic success for students working on computer simulations than when working on experiments, despite a higher cognitive load. The authors concluded that simulations may be more appropriate for teaching complex topics [7]. These results suggest that different imaging methods can affect learning outcomes differently.

Interest and motivation. Computer visualization tools have been proven to increase students' interest and motivation. The results [8] demonstrate the effectiveness of providing didactic care through computer visualization tools, with positive feedback in terms of usability and learning productivity. The interactive nature of tools such as augmented reality facilitates active interaction with educational materials. The impact of visualization on students' interests is especially noticeable. Newby et al. [8] explain that visuals can be eye-catching, provide real-world examples, stimulate thinking or research, increase data processing efficiency, improve comprehension and memory, and illustrate procedures [9].

Cognitive processing and understanding of the material. With the advent of computers and the ability to generate vast amounts of data, visualization makes it possible to use our visual senses. Indeed, other technologies such as statistical analysis, artificial intelligence, mathematical filtering, and sampling theory will play a role in big data processing. However, because imaging directly engages the human visual system and brain, it remains an unrivaled technology for understanding and transmitting data [9]. The direct involvement of the visual system makes visualization a compelling approach to conveying complex information. Computer visualization tools can significantly impact how students process and understand complex information. The authors [5] prove that designing visualization tools based on constructivist learning theories can improve cognitive processing and deep understanding of data.

Discussion. Despite the potential benefits, implementing computer visualization tools in educational institutions faces several challenges. The complexity of developing and using visualization tools can be a significant hurdle. Unfortunately, in technical education, creating complex geometric virtual prototypes, producing videos, or developing websites is often seen as a challenging task, and with a web-centric generation of learners, expectations for visual learning are extremely high [5].

Effective integration of visualization tools requires the analysis of pedagogical approaches. Computer simulations were designed for real-world research, and their adoption requires a justification regarding the goals and methods to achieve them. There are many potential applications for computational simulations, but a theoretically sound foundation is needed to teach students as effectively as possible to help educators use simulations reasonably. Studies have shown that program visualization is effective for students to perform programming exercises or support self-paced learning. However, very few teachers actively use PV tools. The article [20] discussed educators' obstacles when combining PV tools into lecture halls. Understanding and removing the barriers preventing educators from using visualization tools is critical to successfully integrating them into educational practice.

Ensuring equal access to visualization tools remains a significant challenge. All people have the right to access information and use available technologies, but not everyone has the same opportunities [25]. The development of accessible visualization

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tools requires considering the diverse needs of users, including people with various disabilities. The study [25] analyzes potential future research areas related to individual personalization of such solutions. The results of the literature review can contribute to the creation of recommendations on the accessibility of augmented reality and stimulate the development of accessible solutions not only for people with disabilities but also for people without disabilities [25].

Conclusions. A review of the literature reveals a variety of approaches, applications, and results regarding the use of computer imaging tools in education. From app visualization tools to augmented reality applications, these tools have changed how students learn and interact with complex concepts across disciplines. These positive impacts highlight the potential of visualization tools to address some ongoing challenges in education, especially in STEM fields. Integrating visualization tools with new technologies opens up opportunities for educational innovation. New disciplines such as interaction design, human-computer interaction, and user experience are essential for education. The convergence of visualization with interaction design, human-computer interaction, and user experience design opens new opportunities to enhance the learning experience. The future of educational visualization lies in personalization and adaptive approaches. One of the identified research gaps is the lack of personalization in the applications developed, which gives room for future research. Developing visualization tools that adapt to individual needs and learning styles is a promising study area. At the same time, significant challenges remain in the widespread and effective implementation of visualization tools, and the future of visualization in education lies in personalization and integration of visualization with new educational technologies.

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ISSN: 2786-9458

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