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Enhancing digital competence through STEM-integrated universal design for learning: a pedagogical framework for computer science education in Ukrainian secondary schools

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Abstract
This study investigates how integrating STEM content in computer science education enhances the implementation of Universal Design for Learning (UDL) principles and its impact on digital competence development in Ukrainian secondary schools. The digital transformation of education demands innovative pedagogical approaches that accommodate diverse learning needs while developing essential competencies. Through a mixed-methods quasi-experimental design involving 28 computer science teachers (14 specialists, 12 first-category, 12 higher-category) and 200 students from secondary schools in western Ukraine, this study examines whether STEM-oriented content enables more effective UDL implementation compared to traditional computer science content. Both experimental and control groups received UDL-based instruction; however, the experimental group engaged with STEM-integrated content, including robotics and physical computing, while the control group followed traditional computer science topics. Results reveal that STEM integration significantly enhances UDL effectiveness, with the experimental group demonstrating up to 24% greater improvement in digital competencies than the control group. The most pronounced differences appeared in programming competencies (12% vs. 3% increase at expert level) and netiquette (18% vs. 8% increase at advanced level). Integrating STEM content transforms computer science from abstract modelling to physical interaction, fully implementing UDL's three core principles through multiple representations (physical and digital), diverse means of action and expression (building and coding), and enhanced engagement through real-world connections. The study identifies key implementation factors, including teacher preparedness, infrastructure requirements, and content-specific adaptations. These findings provide a pedagogical framework demonstrating that STEM content catalyses more effective UDL implementation, with implications for curriculum design and teacher professional development in countries undergoing educational reform under challenging circumstances.

Keywords Universal design for learning, STEM education, Digital competence, Computer science education, Inclusive pedagogy, Educational innovation, Physical computing, Educational transformation

1 Introduction

The educational landscape is profoundly transforming globally, driven by rapid technological advancement and evolving pedagogical paradigms. In Ukraine, this transformation occurs against significant national challenges, including the ongoing war and the implementation of comprehensive educational reforms. The New Ukrainian School reform, initiated in 2016, represents a fundamental shift toward competency-based learning, emphasising the development of transversal skills necessary for success in the modern digital society [1, 2]. Computer science education plays a pivotal role in this transformation, serving as both a subject domain and a vehicle for developing broader digital competencies essential across disciplines.

Contemporary computer science education faces multiple interconnected challenges. The rapid evolution of digital technologies creates a perpetual gap between educational content and industry practices, requiring continuous curriculum adaptation. Moreover, schools encounter substantial variability in students' prior digital experiences, creating heterogeneous classroom environments that demand differentiated instructional approaches. Implementing STEM (Science, Technology, Engineering, and Mathematics) education further complicates this landscape, requiring students to integrate knowledge across disciplines while developing practical skills in increasingly complex technological environments.

The Ukrainian educational context adds unique dimensions to these challenges. According to recent reports from the Ministry of Education and Science of Ukraine, the ongoing conflict has damaged or destroyed over 2300 educational institutions, disrupting access to educational resources and creating unstable learning conditions for many students [3]. Significant disparities exist in technological infrastructure across regions, with some schools having limited access to modern computing equipment and reliable internet connectivity. These conditions heighten the need for flexible, resilient educational approaches that can function effectively across diverse settings while accommodating varied student needs.

Universal Design for Learning (UDL) offers a promising framework for addressing these multifaceted challenges. Defined as an educational approach that accommodates individual differences in learning by providing multiple means of engagement, representation, and action/expression, UDL aligns with Ukraine's legislative commitment to educational inclusion [4]. The Law of Ukraine "On Education" explicitly recognises universal design as creating educational environments that are maximally accessible to all learners without requiring specialised adaptations [1]. This principle resonates with the core values of the New Ukrainian School reform, which emphasises personalised learning pathways and equal educational opportunities.

The recent introduction of an integrated STEM course as an elective option in the Ukrainian typical curriculum plan [5] creates new opportunities for innovative pedagogical approaches. STEM education and UDL share complementary objectives, with both approaches emphasising flexible problem-solving, multidisciplinary integration, and the application of knowledge in authentic contexts. However, empirical research on their integration within computer science education remains limited, particularly examining how STEM content might enhance UDL implementation effectiveness. This gap is particularly significant given the crucial role of digital competencies in Ukraine's ongoing digital transformation initiatives and economic development strategy.

This study addresses this research gap by examining how integrating STEM content in computer science education enhances the implementation of UDL principles and its subsequent impact on digital competence development in Ukrainian secondary schools. We hypothesise that STEM-oriented content, emphasising physical computing and real-world applications, provides richer opportunities for implementing UDL principles than traditional computer science instruction. Specifically, this research investigates three key research questions:

1. How does integrating STEM content in computer science education enhance the implementation of UDL principles compared to traditional computer science content?
2. What is the differential impact of STEM-integrated UDL instruction versus traditional UDL instruction on students' digital competence development?
3. What factors facilitate or hinder the effective implementation of STEM-integrated UDL in Ukrainian computer science classrooms?

2 Theoretical framework

2.1 STEM education: evolution and conceptual foundations

STEM education represents a paradigm shift from traditional disciplinary silos toward integrated, problem-centered learning that reflects the interconnected nature of modern scientific and technological practice. The conceptual foundations of STEM education have evolved significantly over the past decades, transitioning from coordinated but separate subject instruction to truly interdisciplinary approaches that blur disciplinary boundaries in service of authentic problem-solving.

The historical development of STEM education traces back to educational reforms in the United States during the 1990 s when concerns about international competitiveness in science and technology prompted calls for more integrated and applied approaches to science and mathematics education [6]. Initially focused on enhancing achievement in individual STEM disciplines, the approach gradually evolved toward a more holistic vision emphasising interdisciplinary connections and real-world applications. This evolution reflects a growing recognition that complex contemporary challenges rarely fall within neat disciplinary boundaries and instead require integrated approaches drawing on diverse knowledge domains.

According to the US National Science Foundation (NSF), STEM education fundamentally involves "learning across disciplines", integrating concepts from science, technology, engineering, and mathematics to develop students' ability to identify, apply, and integrate these concepts toward understanding complex problems and developing novel solutions [7]. This definition emphasises the application of knowledge rather than mere acquisition, positioning STEM education as inherently practice-oriented and contextual.

The European Commission's conceptualisation of STEM education similarly emphasises integration while highlighting innovative technologies' role in transforming educational processes [8]. This perspective positions STEM not merely as content to be learned but as an approach to learning that fundamentally transforms how students engage with educational material across disciplinary boundaries [9].

Contemporary STEM education operates through several core principles. First, it emphasises interdisciplinary integration that transcends traditional subject boundaries to develop a holistic understanding of complex phenomena. This integration occurs not through superficial connections between subjects but deep engagement with authentic problems that naturally require multiple disciplinary perspectives. Second, STEM education is fundamentally practice-oriented, focusing on applying knowledge rather than abstract understanding. This reflects the growing recognition that knowledge acquisition disconnected from authentic application has limited value in developing the competencies required in modern workplaces.

Project-based and inquiry-driven methodologies form the pedagogical backbone of effective STEM education [10]. These approaches position students as active knowledge constructors rather than passive recipients, engaging them in extended investigations of meaningful questions through iterative planning, implementation, evaluation, and refinement cycles. Such approaches mirror authentic scientific and engineering practices while developing critical competencies, including collaboration, critical thinking, and problem-solving.

International implementation of STEM education reveals both common principles and contextual adaptations. In Finland, for example, STEM education is deeply integrated with the phenomenon-based learning approach that organises instruction around real-world phenomena rather than academic subjects [11]. This approach has contributed to Finland's consistently strong performance in international assessments like PISA, particularly in scientific literacy. Singapore's STEM implementation emphasises strong fundamentals in individual disciplines while creating extensive opportunities for application through specialised STEM schools and industry partnerships. South Korea has developed a comprehensive STEM pipeline connecting K-12 education with higher education and industry through coordinated national initiatives and specialised STEM academies.

These diverse implementation models share common success factors, including systematic policy support, robust teacher professional development, adequate infrastructure, and strategic partnerships with industry and research institutions. They also reflect common challenges, including assessment difficulties, equity concerns, and balancing disciplinary depth with interdisciplinary breadth.

Implementing STEM education in Ukraine has emerged as a strategic educational priority, particularly following adopting the New Ukrainian School reform in 2016. This reform explicitly identifies STEM education as a key approach for developing students' innovation capabilities and preparing them for successful participation in the knowledge economy [12, 13]. The Ukrainian STEM education concept emphasises the development of research competencies through practical problem-solving while fostering creativity and critical thinking.

The recent ministerial order introducing an integrated STEM course as an elective option in the typical curriculum plan for grades 5–9 marks a significant development in Ukrainian STEM education [5]. This course integrates natural sciences, technology, engineering, and mathematics knowledge through project-based learning and real-world problem-solving. The curriculum emphasises hands-on experimentation, design thinking, and developing 21st-century skills essential for the digital economy.

However, STEM implementation in Ukraine faces distinctive challenges related to infrastructure limitations, traditional pedagogical approaches, and the ongoing impact of the war. A study by Petryk et al. [14] found significant variations in STEM readiness across different regions of Ukraine, with urban schools generally having greater access to necessary resources and teacher expertise. The study also identified teacher professional development as a critical factor in successful STEM implementation, with teachers expressing a particular need for support in interdisciplinary teaching methods and technology integration.

2.2 Universal design for learning: principles and neurocognitive foundations

UDL represents a comprehensive educational framework that aims to optimise teaching and learning for all individuals by addressing the inherent variability in human learning. Developed by the Center for Applied Special Technologies, UDL extends the architectural concept of universal design to educational environments, aiming to create learning experiences that are accessible to all students without requiring specialised adaptations or modifications.

The conceptual foundations of UDL are firmly grounded in neuroscience research that has identified three primary neural networks involved in learning: recognition networks (the “what” of learning), strategic networks (the “how” of learning), and affective networks (the “why” of learning) [15]. Recognition networks are specialised for sensing and assigning meaning to patterns, enabling learners to identify and understand information, ideas, and concepts. Strategic networks coordinate mentalised actions and skills, allowing learners to plan, execute, and self-monitor learning actions. Affective networks evaluate patterns and assign emotional significance, influencing engagement, persistence, and self-regulation in learning.

The seminal research by Rose and Strangman [16] at Harvard University’s Brain Research Center involving over 5000 students established that these neural networks function differently across individuals, creating natural variability in learning processes that traditional “one-size-fits-all” educational approaches fail to accommodate. This research has been further corroborated by recent neuroimaging studies that demonstrate how learners process and respond to educational content through different neural pathways, even when achieving similar learning outcomes.

From these neuroscientific foundations emerge the three core principles of UDL, each addressing a specific neural network. The first principle, providing multiple means of representation, acknowledges variability in how learners perceive and comprehend information. This principle advocates presenting content in diverse formats (visual, auditory, tactile) and providing scaffolds for decoding and comprehension to accommodate different recognition networks. The second principle, providing multiple means of action and expression, addresses variability in strategic networks by offering diverse options for navigating learning environments and demonstrating knowledge. The third principle, providing multiple means of engagement, addresses affective network variability by providing multiple pathways to stimulate interest, maintain effort, and support self-regulation.

Each principle encompasses specific guidelines for implementation, creating a comprehensive framework for designing learning experiences that accommodate learner variability without sacrificing educational rigour. For instance, the first principle includes guidelines for providing options for perception (e.g., customisable display of information), language and symbols (e.g., clarifying vocabulary and syntax), and comprehension (e.g., activating background knowledge). The second principle includes guidelines for providing options for physical action (e.g., varied response methods), expression and communication (e.g., multiple media for communication), and executive functions (e.g., goal-setting support). The third principle encompasses guidelines for providing options for recruiting interest (e.g., optimising relevance and authenticity), sustaining effort and persistence (e.g., varying demands and resources), and self-regulation (e.g., developing self-assessment capacities).

Beyond these core principles, UDL implementation involves several key characteristics that distinguish it from other educational approaches. First, UDL is proactive rather than reactive, designing learning environments from the outset to accommodate diverse learners rather than retrofitting existing environments in response to specific needs. Second, UDL focuses on removing barriers within the educational environment rather than "fixing" perceived deficits within learners. Third, UDL emphasises flexibility and choice within structured learning environments, providing options within carefully designed parameters rather than unlimited freedom that might overwhelm learners.

The effectiveness of UDL implementation has been documented across diverse educational contexts. A meta-analysis by Almeqdad et al. [17] examining empirical peer-reviewed research from 2015 to 2021 found statistically significant effects of UDL principles on learning outcomes across diverse educational settings. The analysis revealed powerful effects for interventions that addressed multiple UDL principles simultaneously and were implemented with fidelity over extended periods.

Research specifically examining UDL in STEM education contexts has yielded promising findings. Studies demonstrate that UDL implementations in STEM classrooms can increase student engagement, improve learning outcomes, and reduce performance gaps between different student groups [18]. Applying UDL principles appears particularly beneficial in STEM disciplines due to the abstract nature of many STEM concepts and the diverse representational formats used in STEM fields. Schref-fler et al. [19] found that UDL implementation in STEM contexts supported not only academic achievement but also the development of self-advocacy skills and increased persistence in challenging content areas.

However, UDL implementation also faces challenges, particularly in educational systems with strong traditions of standardised approaches. A critical analysis by Anastasiou et al. [20] identifies several potential limitations, including the difficulty of operationalising UDL principles in assessment contexts, the potential conflict between multiple means of representation and cognitive load theory, and the challenge of distinguishing between essential variability accommodation and appropriate cognitive challenge. These critiques highlight the need for thoughtful, context-sensitive implementation of UDL principles rather than formulaic application.

In the Ukrainian educational context, UDL has gained increasing recognition as an approach aligned with the inclusive values of the New Ukrainian School reform. The concept of universal design is explicitly mentioned in the Law of Ukraine "On Education" and related regulatory documents, reflecting growing awareness of the need to accommodate learner diversity in educational settings [1]. The New Ukrainian School Concept explicitly emphasises creating inclusive educational environments that support all learners, including those with special educational needs, through flexible pedagogical approaches and differentiated instruction [2]. However, systematic research on UDL implementation in Ukrainian educational contexts remains limited, particularly regarding STEM education integration.

2.3 The synergy of STEM and UDL: theoretical foundations for integration

Integrating STEM education and UDL principles represents more than a simple combination of two educational approaches; it creates a synergistic framework where each approach enhances the effectiveness of the other. This section develops the theoretical rationale for why STEM content, particularly in computer science education, provides an optimal context for implementing UDL principles while UDL principles enable more effective STEM learning for diverse students.

2.3.1 STEM content as an enabler of UDL implementation

Traditional computer science education often remains confined to abstract representations on screens, limiting how students can engage with and demonstrate their understanding of computational concepts. Integrating STEM content, particularly through physical computing, robotics, and engineering design, fundamentally transforms the learning landscape by expanding the modalities through which students can interact with computational ideas.

The first UDL principle, multiple means of representation, gains enhanced expression through STEM integration. Where traditional computer science might represent an algorithm solely through code or flowcharts, STEM-integrated approaches allow students to see algorithms enacted through robot movements, sensor responses, or physical constructions. For instance, a sorting algorithm can be represented through pseudocode and physical manipulation of objects by a robotic arm, providing tactile and visual learners with additional pathways to understanding. This multiplication of representational modes directly addresses the recognition network variability that UDL seeks to accommodate.

The second UDL principle, multiple means of action and expression, finds natural extension through STEM activities. Physical computing allows students to demonstrate their understanding through building, wiring, and programming tangible artefacts. A student who struggles with traditional coding syntax might excel at designing physical circuits or constructing mechanical systems that embody computational thinking principles. This expansion of expression modalities is not merely additive; it transforms the nature of what counts as demonstrating computational competence.

The third UDL principle, multiple means of engagement, benefits significantly from the real-world relevance of STEM integration. Abstract programming exercises often fail to engage students who do not see their practical application. However, programming a robot to navigate a maze, designing an environmental monitoring system, or creating an automated greenhouse connects computational thinking to tangible, meaningful outcomes. This connection to physical reality enhances motivation and sustains engagement, particularly for students who learn best through concrete applications.

2.3.2 UDL as a framework for effective STEM implementation

While STEM content enhances UDL implementation, UDL principles simultaneously address critical challenges in STEM education. STEM subjects are often perceived as difficult and inaccessible, particularly for students who do not fit the traditional profile of STEM learners. UDL principles provide a structured approach to making STEM content more accessible without reducing its rigour or complexity.

Applying UDL to STEM education addresses the well-documented challenge of STEM accessibility. Research has shown that many students, particularly those from under-represented groups, face barriers in STEM learning related to prior knowledge gaps, language challenges, and cultural relevance [21]. UDL's emphasis on removing environmental barriers rather than remediating student deficits aligns with the contemporary understanding of STEM equity issues.

Furthermore, the complexity of integrated STEM learning, which requires students to coordinate knowledge across multiple disciplines, benefits from UDL's structured approach to scaffolding. The UDL framework guides breaking down complex, multidisciplinary problems into manageable components while maintaining their authentic, integrated nature. This scaffolding is essential for STEM education, where the cognitive load of managing multiple disciplinary perspectives can overwhelm students.

2.3.3 Theoretical model of STEM-UDL integration

Based on this analysis, we propose a theoretical model where STEM content and UDL principles exist in a mutually reinforcing relationship within computer science education. In this model:

1. *STEM content expands the design space for UDL implementation* by providing additional modalities for representation, action, and engagement that are not available in traditional computer science instruction.
2. *UDL principles provide the pedagogical framework* for making STEM content accessible to diverse learners, ensuring that the increased complexity of integrated learning does not create new barriers.
3. *The combination creates emergent properties* where the whole is greater than the sum of its parts, enabling learning experiences that neither approach could achieve independently.

This theoretical model predicts that computer science instruction integrating STEM content within a UDL framework will improve student learning outcomes more than traditional computer science instruction with UDL or STEM-integrated instruction without UDL principles. The model also suggests that the benefits will be most pronounced for students who face barriers in traditional instructional approaches as they gain access to multiple pathways for learning and expression.

2.4 Integration of STEM and UDL in computer science education

Integrating STEM education and UDL in computer science contexts represents a promising intersection with potential benefits for diverse learners. Computer science's emphasis on computational thinking, problem-solving, and technological applications naturally aligns with STEM's interdisciplinary approach. Similarly, the digital nature of computer science content offers unique opportunities for implementing UDL principles through adaptable digital technologies and flexible representation formats.

Research on this integration has emerged from several complementary perspectives. First, studies have examined how computational thinking can be effectively integrated into broader STEM education. A systematic literature review by Wang et al. [22] identified various instructional models for integrating computational thinking in STEM contexts, with problem-based instruction emerging as the most common approach. The review found that game design, robotics, and computational modelling provided particularly effective contexts for this integration, creating authentic learning environments that naturally blend computational thinking with other STEM disciplines.

The effectiveness of this integration has been empirically supported through recent meta-analytic work. Cheng et al. [23] conducted a meta-analysis of studies examining the effects of computational thinking integration in STEM on K-12 students' learning performance. This analysis revealed a statistically significant large effect size (g = 0.85), indicating substantial benefits from integrating computational thinking into STEM education. The effect was moderated by intervention duration, suggesting the importance of sustained, rather than episodic, integration efforts.

From the UDL perspective, research has examined how the framework can be explicitly applied to computer science and broader STEM education. A systematic literature review by Schreffler et al. [19] found that UDL implementation in postsecondary STEM education for students with disabilities resulted in increased inclusive teaching methods and enhanced self-advocacy among students. However, the review also noted the limited number of empirical studies in this area, highlighting the need for further research on UDL implementation in STEM contexts.

Integrating UDL principles in computer science education presents unique opportunities and challenges. Computer science content can be represented through multiple means, including visual programming environments, textual code, pseudocode, flowcharts, and interactive simulations, aligning with UDL's first principle of multiple means of representation. Similarly, computer science offers various means of expression, from different programming languages to visual design tools, supporting UDL's second principle. The authentic problem-solving nature of computer science can enhance engagement, supporting the third UDL principle, but requires careful scaffolding to maintain accessibility for diverse learners.

Digital tools play a critical role in this integration. Research by Harris et al [24] demonstrates how digital technologies can foster student engagement within the UDL framework, presenting case studies of higher education classrooms where technology-enhanced UDL implementation created more flexible and inclusive learning environments. The study emphasises that effective technology integration must be guided by UDL principles rather than technology for its own sake, focusing on how digital tools can reduce barriers to learning rather than introducing new ones.

Digital competence frameworks provide essential reference points for understanding the skills integrated STEM and UDL approaches aim to develop in computer science education. The European Digital Competence Framework (DigComp), now in version 2.2, identifies five competence areas: information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving [25]. This framework has been adapted for educational contexts through DigCompEdu, which focuses on educators' digital competencies to implement compelling digital learning experiences.

A comparative analysis of international digital competence frameworks by Mattar et al. [26] found common competence areas across frameworks, including communication, collaboration, information management, content creation, technical skills, and ethical considerations. The analysis highlighted the importance of segmenting frameworks by educational actors (students, teachers, administrators) and educational levels to provide targeted guidance for competence development.

In the Ukrainian context, digital competence development has become a priority within the broader educational reform process. Research by Vakaliuk and Antoniuk [27] found increasing adoption of cloud services and digital technologies in Ukrainian secondary education, with positive trends in using ICT tools in education. However, the study also identified challenges related to teacher preparation and infrastructure limitations that impact effective digital competence development.

Integrating STEM and UDL approaches in computer science education requires thoughtful consideration of pedagogical strategies that support interdisciplinary learning and universal accessibility. Siiman et al. [28] proposed using integrative STEM as a framework for developing digital literacy for all students, highlighting robotics and 3D computer software as promising platforms for this integration. This approach emphasises how authentic engineering design and scientific inquiry activities can naturally incorporate digital literacy development when structured according to universal design principles.

Recent research has begun examining how culturally responsive pedagogy can be combined with UDL in computer science education, recognising the importance of cultural relevance and accessibility. Century andWeisberg [29] described ongoing work to develop a component-based research approach for studying and communicating these integrated pedagogical approaches in elementary computer science education, highlighting the need for specified language and frameworks to accumulate knowledge about these complex educational interventions.

The intersection of UDL and computational thinking presents particular promise for creating accessible and effective STEM learning experiences. Research by Ehsan et al. [30] examining K-2 students' computational thinking engagement in formal and informal learning settings found that young children can engage with computational thinking across various contexts. The study identified similarities in computational thinking engagement across settings, with competencies including abstraction, algorithm development, debugging, pattern recognition, and simulation appearing in formal and informal environments. This suggests the potential for designing coherent educational experiences that support computational thinking development across learning contexts, a goal that aligns with UDL's emphasis on flexible, accessible learning environments.

Implementing integrated STEM and UDL approaches in computer science education requires systematic planning and appropriate scaffolding. Wong [31] described an exploratory study of integrated STEM education in a Hong Kong primary school, highlighting the challenges and opportunities of implementing such programs. The study emphasised the importance of teacher preparation, administrative support, and appropriate curriculum materials for successful implementation. These findings align with research on UDL implementation, which similarly emphasises the importance of systematic support structures rather than isolated classroom interventions.

2.5 STEM and UDL in the Ukrainian educational context

The implementation of STEM education and UDL in Ukraine occurs within a distinct educational context characterised by ongoing reform efforts, significant regional variations, and the war's profound impact. Understanding this context is essential for analysing how these educational approaches can effectively adapt to Ukrainian realities.

The New Ukrainian School reform, initiated in 2016, represents Ukraine's most comprehensive educational transformation since its independence. As described by Hrynevych et al. [32], this reform aims to modernise the educational system by focusing on competency-based learning, safe learning environments, inclusion, and digitalisation. The reform's conceptual framework draws on advanced pedagogical practices and European competency frameworks while emphasising Ukrainian national values and priorities.

The reform has included extensive piloting efforts to test new content and methodologies before nationwide implementation. According to Hrynevych et al. [32], the reform was initially piloted in 143 schools representing a cross-section of Ukrainian educational institutions, allowing for methodical evaluation and refinement before broader implementation. Research by Kremen et al. [4] has identified key factors influencing educational quality in the context of the reform, with particular emphasis on internal factors like mean years of schooling and R&D expenditure.

STEM education has been identified as a strategic priority within this reform context. Kudria et al. [9] describe the role of innovative techniques in developing STEM education in Ukraine, highlighting approaches such as project-based learning, inquiry-based learning, case studies, collaborative learning, and technology-enhanced methodologies. Their research indicates that these approaches help address challenges in implementing STEM education and contribute to preparing students for real-world problem-solving.

The formal introduction of integrated STEM education through ministerial order represents a significant milestone in Ukrainian educational policy. The typical curriculum plan now includes an integrated STEM course as an elective option for grades 5–9, allowing schools to offer interdisciplinary STEM learning experiences within the formal curriculum structure [5]. This development provides an institutional framework for the kind of integrated learning that our study examines.

The organisation of educational space plays a crucial role in implementing STEM education and UDL principles. Bilousova et al. [12] describe the organisation of educational space in the New Ukrainian School, emphasising how this physical environment influences cognitive, aesthetic, and ethical development. Their research highlights the importance of creating flexible learning environments that accommodate different learning activities and student needs, aligning with core UDL principles.

The use of digital technologies in Ukrainian education has increased significantly in recent years, partly in response to the challenges posed by the COVID-19 pandemic and the war. Research by Vakaliuk and Antoniuk [27] analysing the use of digital technology in general secondary education in Ukraine found positive dynamics in adopting various ICT tools, with teachers increasingly incorporating digital resources into their teaching.

The study, based on surveys of first-year university students, suggests gradually improving digital infrastructure and pedagogical approaches to technology integration.

Computer science education in Ukraine has seen notable developments, particularly regarding integrating innovative technologies. Proskura et al. [33] describe the use of web-oriented technologies in programming education at technical universities, highlighting how these approaches prepare students for the demands of Ukraine's growing IT sector. Their research found that 76.7% of graduating students were already employed in IT companies, suggesting the effectiveness of current approaches in developing industry-relevant skills.

The challenges of war have necessitated innovative approaches to maintaining educational continuity. Stupak et al. [34] describe the development of IoT-based virtual models for laboratory practice, created in response to limitations on physical access to educational facilities. This approach exemplifies how virtual environments can provide practical educational experiences when traditional infrastructure is unavailable, a reality facing many Ukrainian educational institutions due to safety concerns or physical damage.

The impact of the Russian invasion on Ukraine's educational system has been profound. Agapova [35] highlights the detrimental effects on educational infrastructure and the broader learning environment, calling for international support to build educational resilience. Similarly, Hrynevych [3] describes the emergency responses of the Ukrainian school education system to the full-scale invasion, including measures to restore access to education, establish digital learning centres, enhance distance education quality, address educational losses, and support psychological well-being.

Within this challenging context, implementing UDL principles offers potential benefits while facing significant barriers. Grillo [36] describes the administrator's role in successful UDL implementation, emphasising the importance of creating inclusive school cultures and providing instructional leadership. While this research was not specific to Ukraine, its insights regarding the importance of administrative support and inclusive school cultures are relevant for Ukrainian educational leaders implementing UDL approaches.

The implementation of UDL in low- and middle-income countries, a category that includes Ukraine, presents both challenges and opportunities. Research by McKenzie et al. [37] found that while UDL concepts are not entirely new in these contexts, their formal implementation requires adaptation to local realities. The study emphasised the importance of mainstreaming UDL in teacher training programs and adapting implementation approaches to respond to contextual factors rather than directly importing approaches developed in high-income countries.

The intersection of STEM education and UDL principles in the Ukrainian context remains under-researched, particularly regarding computer science education. However, the alignment between the inclusive values of the New Ukrainian School reform and UDL principles, combined with the strategic emphasis on STEM education, suggests potential for productive integration. Pidhurska et al. [38] describes innovative technologies for developing various competencies in Ukrainian primary education, highlighting approaches that align with STEM and UDL principles, such as game-based learning and multimedia approaches.

Pre-service teacher preparation is critical in implementing STEM education and UDL principles effectively. Research by Petryk et al. [14] examining pre-service teachers' perceptions of STEM education in Ukraine found positive attitudes but significant variations across specialities. The study identified several barriers to effective STEM implementation, including limited resources, insufficient teacher knowledge, and lack of appropriate teaching materials. These findings suggest the importance of targeted professional development to support the integration of STEM and UDL approaches in Ukrainian education.

3 Research methodology

3.1 Research questions and hypotheses

Based on the theoretical framework and the identified gaps in current understanding, this study addresses the following research questions:

RQ1: How does integrating STEM content in computer science education enhance the implementation of UDL principles compared to traditional computer science content?

RQ2: What is the differential impact of STEM-integrated UDL instruction versus traditional UDL instruction on students' digital competence development?

RQ3: What factors facilitate or hinder the effective implementation of STEM-integrated UDL in Ukrainian computer science classrooms?

Based on our theoretical model of STEM-UDL synergy, we hypothesise that:

H1: STEM-integrated content will enable a more comprehensive implementation of UDL principles compared to traditional computer science content, particularly in providing multiple means of representation and action/expression.

H2: Students receiving STEM-integrated UDL instruction will show significantly greater digital competence improvements than students receiving traditional UDL instruction, with the largest effects in programming and problem-solving domains.

H3: The effectiveness of STEM-integrated UDL implementation will be moderated by teacher factors (prior inclusive education experience, technical skills), school factors (infrastructure, administrative support), and content factors (topic complexity, physical computing requirements).

3.2 Research design

This study employed a mixed-methods quasi-experimental design combining quantitative and qualitative approaches to investigate the implementation and effectiveness of STEM-integrated UDL principles in computer science education. The mixed-methods approach was selected to provide complementary perspectives on the complex educational phenomena under study, allowing for both measurement of educational outcomes and an in-depth understanding of implementation processes.

The research followed a concurrent triangulation design, with quantitative and qualitative data collected simultaneously and integrated during the analysis phase. This design facilitated the corroboration of findings across methods while providing a comprehensive picture of outcomes and processes. The quantitative component employed a quasi-experimental approach with a pretest-posttest comparison between experimental and control groups, while the qualitative component utilised structured interviews, classroom observations, and document analysis to explore implementation processes and contextual factors.

Notably, both experimental and control groups received instruction based on UDL principles. The key difference was in the content: the experimental group engaged with STEM-integrated computer science topics (including robotics, physical computing, and engineering design), while the control group studied traditional computer science topics (focusing on software-based programming and digital applications). This design allowed us to isolate the effect of STEM content on UDL implementation effectiveness.

The study was conducted during the 2023–2024 academic year in several stages: (1) initial assessment of digital competencies and planning of interventions; (2) implementation of UDL principles in both experimental and control group classrooms with differentiated content; (3) continuous monitoring and documentation of implementation processes; (4) final assessment of digital competencies; and (5) data analysis and interpretation. This timeline allowed for implementation over a sufficient duration to observe meaningful changes in student competencies while remaining practical within the constraints of the academic year.

3.3 Participants and setting

The study involved 28 computer science teachers and 200 students from secondary education institutions in the western regions of Ukraine. This geographic focus ensured relatively consistent educational conditions regarding security situation, organisation of training (offline), and access to learning resources, including electricity availability. These factors were particularly important given the ongoing impact of the war on educational infrastructure in other regions of Ukraine.

Teachers participating in the study represented diverse professional backgrounds, with teaching experience ranging from 3 to 25 years ($M = 12.5$, $SD = 5.8$). The teacher sample included three qualification categories as defined by the Ukrainian educational system: 4 specialists (14.3%), 12 first-category teachers (42.9%), and 12 higher-category teachers (42.9%). This distribution represented the typical qualification structure in Ukrainian secondary schools and ensured that findings would be relevant across different teacher experience levels and expertise (Fig. 1).

Student participants were balanced regarding age ($M = 14.3$, $SD = 0.7$) and gender distribution, with 96 female students (48%) and 104 male students (52%). Students were assigned to experimental and control groups using stratified random sampling to ensure comparable baseline characteristics between groups. Each group included 100 students,

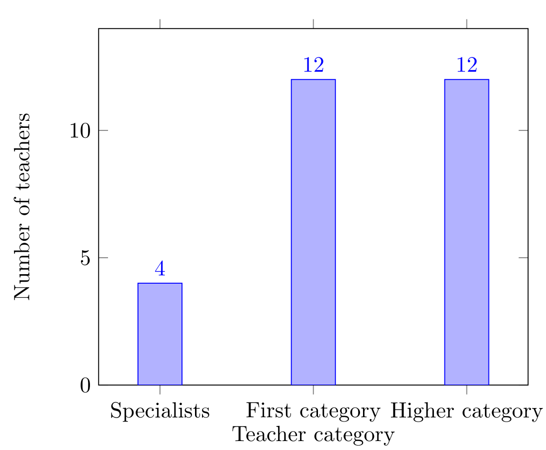

Fig. 1 Distribution of participating teachers by qualification category

providing sufficient statistical power for detecting meaningful effects based on a priori power analysis (power = 0.85 for detecting medium effect sizes with $\alpha = 0.05$) (Fig. 2).

We assessed students' initial digital competence levels across both groups to ensure group equivalence. The distribution of baseline competence levels showed no significant differences between experimental and control groups ($\chi^2 = 2.14$, $p = 0.71$), confirming successful randomisation.

The participating schools represented typical Ukrainian secondary education institutions with standard computer science facilities, including computer laboratories with internet access. While the technological infrastructure varied somewhat across schools, all met the basic requirements for implementing the computer science curriculum according to national standards. Schools were selected to ensure they had sufficient resources to support traditional computer science instruction and STEM-integrated activities, including access to basic robotics kits and microcontroller boards for the experimental group.

3.4 Intervention design

3.4.1 Common UDL framework

Both experimental and control groups received instruction designed according to UDL principles, ensuring that all students benefited from inclusive pedagogical approaches. Teachers in both groups received identical training on UDL implementation, covering:

- The three core UDL principles and their application in computer science education
- Strategies for providing multiple means of representation (visual, auditory, and kinesthetic approaches)
- Techniques for offering multiple means of action and expression
- Methods for ensuring multiple means of engagement
- Assessment strategies aligned with UDL principles

3.4.2 Differentiated content

The key difference between groups lay in the content and activities used to teach computer science concepts:

- **Control group (Traditional UDL):** students engaged with standard computer science topics including:
  - Algorithm development using flowcharts and pseudocode
  - Programming in visual environments (Scratch) and text-based languages (Python)

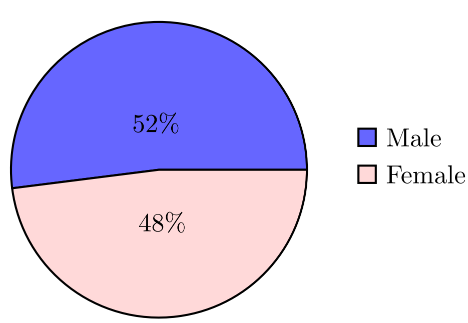

Fig. 2 Gender distribution of student participants

- Database concepts and information systems
- Web development basics
- Digital citizenship and online safety

These topics were taught using UDL principles but remained within the traditional boundaries of screen-based computing.

- **Experimental group (STEM-integrated UDL):** students covered similar computational concepts but through STEM-integrated activities:
  - Algorithm development through robot navigation and sensor-based decision-making
  - Programming using Arduino microcontrollers to control physical devices
  - Data collection and analysis from environmental sensors
  - Engineering design process for creating automated solutions
  - Digital citizenship through IoT security and ethical considerations

For example, while both groups learned about conditional statements, the control group worked with on-screen simulations, while the experimental group programmed robots to respond to physical obstacles using ultrasonic sensors.

3.5 Instruments and measures

3.5.1 Digital competence assessment

Students' digital competencies were assessed using an adapted version of the European Digital Competence Framework for Citizens (DigComp 2.1). This framework was selected due to its comprehensive coverage of digital competence domains and its established use in European educational contexts, including Ukraine [39]. The adaptation maintained the framework's five competence areas (information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving) while adjusting language and examples to be appropriate for the Ukrainian secondary education context.

The assessment included both self-evaluation components and performance tasks to provide a comprehensive picture of student competencies. The self-evaluation component used a five-level proficiency scale aligned with DigComp 2.1 levels: basic, intermediate, sufficient, advanced, and expert. Students indicated their perceived proficiency level for each competence area using descriptors that specified concrete abilities at each level.

Performance tasks were designed to assess the practical application of digital competencies in authentic contexts, focusing particularly on four key areas relevant to the computer science curriculum: (1) browsing, searching, and filtering data, information, and digital content; (2) evaluating data, information, and digital content; (3) netiquette; and (4) programming. These tasks were reviewed by a panel of five computer science education experts to ensure content validity and appropriate difficulty levels for the target age group.

3.5.2 Universal design implementation scale

The implementation of UDL principles was assessed using a validated Universal Design Implementation (UDI) scale with a reliability index of Cronbach's $\alpha = 0.89$. This instrument measured the extent to which seven key principles of universal design were implemented in educational settings: (1) equality and accessibility of use; (2) flexibility of use; (3) simplicity and ease of use; (4) accessibly presented information; (5) tolerance for errors; (6) low physical effort; and (7) availability of necessary size, place, and space.

For each principle, the scale included multiple items assessing specific implementation aspects using a 5-point Likert scale ranging from "not implemented" to "fully implemented". The scale was completed by both teachers (self-assessment) and researchers (based on classroom observations) to provide multiple perspectives on implementation fidelity.

3.5.3 STEM observation protocol

Classroom observations utilised a structured STEM observation protocol that documented the integration of STEM principles in computer science instruction. The protocol focused on four key dimensions: (1) content integration across STEM disciplines, (2) inquiry-based and problem-centred instructional approaches, (3) student engagement in authentic problem-solving, and (4) use of technology to enhance learning. For each dimension, observers documented specific implementation examples and rated the quality of implementation on a 4-point scale from "not observed" to "highly effective implementation".

3.5.4 Interviews and questionnaires

Structured interviews with teachers explored their experiences implementing UDL principles in STEM-oriented computer science education. The protocol included questions about implementation strategies, perceived benefits and challenges, adaptations to address student needs, and suggestions for improving implementation. The interviews were audio-recorded and transcribed for analysis.

Student questionnaires collected information about learning experiences, perceived accessibility of educational materials, engagement with learning activities, and self-reported learning outcomes. The questionnaire included both closed-ended items using Likert scales and open-ended questions, allowing for more detailed responses about specific aspects of the learning experience.

3.6 Implementation of UDL principles

UDL principles were implemented according to the seven core principles of universal design, with specific adaptations based on whether STEM-integrated or traditional content was being taught.

3.6.1 Equality and accessibility of use

This principle was implemented by providing diverse learning resources addressing different learning styles and needs. Each topic was presented using multiple modalities, including interactive exercises, video materials, text resources with visual support, and hands-on activities.

In the control group, students could select from screen-based options: visual programming environments, text editors with syntax highlighting, interactive tutorials, and video demonstrations. Materials were available at three complexity levels, allowing students to choose appropriate challenges.

In the experimental group, the same principle was enhanced through physical computing options. Students could work with visual programming for robots, text-based Arduino programming, physical circuit construction, or mechanical design activities. The multiple modalities extended beyond the screen to include tactile and kinesthetic options.

3.6.2 Flexibility of use

Flexibility was embedded through varied tasks and assessment options accommodating different learning approaches. Both groups offered choices between individual work, pair programming, small group projects, and whole-class discussions.

The control group provided flexibility through programming languages (Scratch or Python), project themes, and output formats (programs, presentations, or reports). The experimental group expanded these choices to include building physical prototypes, creating sensor-based systems, or designing mechanical solutions, providing additional pathways for students who excel in hands-on activities.

3.6.3 Simplicity and ease of use

To ensure the accessibility of complex computer science concepts, information was presented in clear, straightforward language with consistent terminology. Technical jargon was explained through glossaries and visual aids, and complex processes were broken down into manageable steps.

Both groups benefited from scaffolded instruction, but the experimental group had the advantage of physical demonstrations. Abstract concepts like loops and conditionals became tangible when students could see a robot repeat actions or change behaviour based on sensor input. This physical manifestation of abstract concepts provided an additional understanding for students who struggled with purely symbolic representations.

3.6.4 Accessibly presented information

The content was presented in multimodal formats, ensuring information accessibility. Key concepts were presented through text, images, videos, and interactive demonstrations. Digital materials were designed for compatibility with screen readers and other assistive technologies.

The experimental group had additional representational resources through physical demonstrations and hands-on exploration. For instance, data structures could be represented through diagrams and physical arrangements of objects manipulated by robotic systems, providing multiple pathways to understanding.

3.6.5 Tolerance for errors

Creating an environment where mistakes are viewed as opportunities for learning was essential, particularly for complex topics like programming. Both groups emphasised debugging as a natural part of the programming process.

The experimental group's use of physical computing naturally reinforced this principle. When a robot failed to navigate correctly or a sensor did not respond as expected, the error was immediately visible and often amusing rather than frustrating. This tangible feedback made errors less abstract and more approachable, encouraging experimentation and iterative improvement.

3.6.6 Low physical effort

Both groups considered physical comfort and accessibility through ergonomic workstation setups and regular breaks. The experimental group required additional considerations for handling physical components, with activities designed to minimise fine motor demands and provide alternatives for students with physical limitations.

3.6.7 Availability of necessary size, place, and space

Both groups benefited from flexible classroom arrangements. The experimental group required additional space for robotics activities and component storage, which was accommodated through mobile workstations and designated activity zones.

3.7 Data collection procedures

Data collection followed a systematic protocol to capture implementation processes and educational outcomes. At the beginning of the study, students' digital competencies were assessed using the adapted DigComp 2.1 framework. This assessment established baseline competency levels for both experimental and control groups.

Classroom observations using the STEM Observation Protocol were conducted twice monthly throughout the implementation. Observations were scheduled to capture a representative sample of instructional activities across different topics in the computer science curriculum. Two trained observers conducted each observation independently, with inter-rater reliability assessed regularly to ensure consistency (Cohen's $\kappa = 0.854$).

Teacher interviews were conducted at the midpoint and conclusion of the implementation period, providing insights into implementation processes, challenges, and adaptations. Interviews followed a semi-structured protocol that allowed for consistent coverage of key topics while permitting flexible exploration of issues raised by participants.

Student questionnaires were administered after implementation to collect information about learning experiences and perceived outcomes. The questionnaires were completed electronically, with provisions for privacy and anonymity to encourage candid responses.

The final assessment of digital competencies was conducted during the final two weeks of the implementation period, using the same instruments as the initial assessment. This allowed for a direct comparison of pre- and post-implementation competency levels.

The pedagogical councils approved all participating institutions' data collection procedures, and informed consent was obtained from all participants. Additional parental consent was secured for minor students. Participants were informed about the purpose of the study, the voluntary nature of participation, and confidentiality provisions.

3.8 Data analysis

Data analysis employed a mixed-methods approach integrating quantitative and qualitative findings to understand implementation processes and outcomes comprehensively.

Quantitative data from the digital competence assessments were analysed using descriptive and inferential statistics. Descriptive statistics (frequencies, means, standard deviations) provided an overview of competency levels before and after implementation.

The Shapiro-Wilk test confirmed non-normal distributions for competency-level data, leading to non-parametric tests for group comparisons.

Mann–Whitney U tests compared competency level changes between experimental and control groups. Effect sizes were calculated using Cohen's *d* to determine the practical significance of observed differences. χ^2 tests examined the distribution of students across competency levels. Subgroup analyses examined whether implementation effects varied by gender, baseline competency level, or teacher category.

Qualitative data from interviews, open-ended questionnaire responses, and observation notes were analysed using thematic content analysis. Analysis began with open coding to identify emergent themes, followed by axial coding to establish relationships between themes and selective coding to integrate themes into a coherent framework. The NVivo 14 software facilitated the organisation and analysis of qualitative data.

Two researchers independently coded a subset of qualitative data to establish intercoder reliability (Cohen's $\kappa = 0.85$), with discrepancies resolved through discussion to refine the coding framework. The coding framework was then applied to the whole dataset, with regular checks to ensure consistent application.

Integration of quantitative and qualitative findings occurred through several mechanisms. First, qualitative findings provided explanatory context for quantitative results, helping to understand the processes that produced observed competency changes. Second, quantitative data helped verify and contextualise qualitative analysis themes. Third, case studies integrating both data types were developed to illustrate how STEM content enhanced UDL implementation and affected student learning in specific contexts.

4 Results

4.1 Implementation of UDL principles: comparing traditional and STEM-integrated approaches

The analysis of classroom observations and teacher interviews revealed that while both groups successfully implemented UDL principles, the experimental group achieved more comprehensive implementation, particularly for principles requiring diverse interaction modalities. Table 1 presents the mean implementation ratings for each UDL principle based on the Universal Design Implementation Scale.

The experimental group showed significantly higher implementation ratings for principles directly enhanced by STEM content: equality and accessibility of use, flexibility of use, simplicity and ease of use, and accessibly presented information. These differences reflect how physical computing and robotics naturally provide additional modalities for learning and expression.

Table 1 Implementation ratings of UDL principles by group

UDL principle	Control group		Experimental group		*p*-value
	Mean	SD	Mean	SD	
Equality and accessibility of use	3.8	0.7	4.4	0.5	0.012*
Flexibility of use	3.5	0.8	4.2	0.6	0.008**
Simplicity and ease of use	4.1	0.6	4.5	0.4	0.045*
Accessibly presented information	3.7	0.7	4.3	0.5	0.015*
Tolerance for errors	3.9	0.8	4.1	0.7	0.342
Low physical effort	3.8	0.7	3.6	0.9	0.523
Availability of necessary size, place, and space	3.6	0.9	3.7	1.0	0.741

Note. Ratings based on 5-point scale where 1 = Not implemented, 5 = Fully implemented

Qualitative analysis revealed specific ways STEM content enhanced UDL implementation:

- **Enhanced multiple representations:** teachers in the experimental group reported that physical computing provided powerful additional representations for abstract concepts. One teacher explained:

When teaching loops, I can show the code and draw the flowchart, and then students can see the robot actually repeating actions. Some students who struggled with understanding loops on screen immediately grasped it when they saw the physical repetition. The 'aha' moments were remarkable. (Teacher E7)

- **Expanded expression options:** STEM integration gave students more ways to demonstrate their understanding. While control group students could express learning through code, diagrams, or written explanations, experimental group students could build physical systems, create mechanical solutions, or design sensor-based interactions.
- **Increased engagement through relevance:** The tangible nature of STEM projects enhanced student engagement by making abstract concepts concrete and relevant. A teacher noted:

Students who previously asked, 'Why do we need to learn this?' became deeply engaged when programming greenhouse monitoring systems or designing automated pet feeders. The physical outcomes made the learning meaningful. (Teacher E12)

Classroom observations documented that 82% of lessons in the experimental group incorporated physical manipulation or construction activities, compared to 0% in the control group. This fundamental difference in learning modalities explains the enhanced implementation ratings for accessibility and flexibility principles.

4.2 Impact on digital competence development

Analysis of pre- and post-implementation digital competence assessments revealed that while both groups improved, the experimental group showed significantly greater gains across all competence areas. Table 2 presents the percentage of students at each competence level before and after implementation.

The experimental group demonstrated consistently larger improvements, with the most substantial differences in programming and netiquette competencies. Statistical analysis using Mann–Whitney U tests confirmed significant differences between groups in post-implementation competency distributions for all four areas (all $p < 0.01$).

4.2.1 Programming competence: the power of physical computing

The most pronounced differences appeared in programming competencies, where the experimental group showed a 17.5% decrease in students at the basic level compared to only 6% in the control group. More importantly, 12% of experimental group students moved to the expert level compared to just 3% in the control group.

Figure 3 illustrates these dramatic differences in programming competence development.

Table 2 Changes in digital competence levels by group and domain (% of students)

Competence area and level	Control group			Experimental group		
	Pre	Post	Change	Pre	Post	Change
Browse, search, and filter data						
Basic	30	26	−4	31	23	−8
Intermediate	20	18	−2	20	13	−7
Sufficient	15	17	+2	13	20	+7
Advanced	20	21	+1	20	24	+4
Expert	15	16	+1	16	20	+4
Evaluation of data and digital content						
Basic	36	30	−6	36	26	−10
Intermediate	16	14	−2	17	14	−3
Sufficient	15	17	+2	14	16	+2
Advanced	22	24	+2	21	26	+5
Expert	11	15	+4	12	18	+6
Netiquette						
Basic	30	20	−10	30	15	−15
Intermediate	17	14	−3	16	10	−6
Sufficient	17	22	+5	18	20	+2
Advanced	16	24	+8	15	33	+18
Expert	20	20	0	21	22	+1
Programming						
Basic	36	30	−6	37	19.5	−17.5
Intermediate	22	17.5	−4.5	22.5	18.5	−4
Sufficient	18	21.5	+3.5	18.5	21	+2.5
Advanced	10	14	+4	10	17	+7
Expert	14	17	+3	12	24	+12

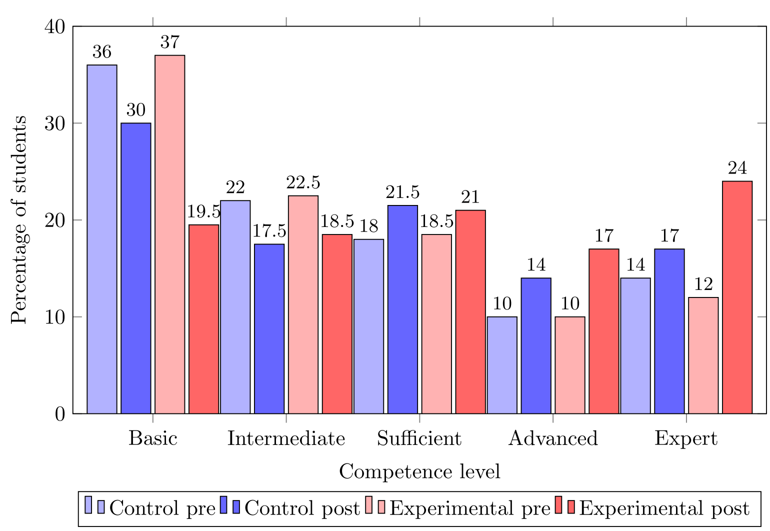

Fig. 3 Changes in programming competence level distribution

Effect size calculations revealed large effects for the experimental group (Cohen's $d = 0.82$) compared to medium effects for the control group ($d = 0.41$), indicating that STEM integration substantially enhanced programming skill development.

Qualitative data provided insights into why physical computing enhanced programming competence:

Table 3 Detailed results for "Browse, search, and filter data" competence

Competence descriptor	Control group		Experimental group	
	Pre (%)	Post (%)	Pre (%)	Post (%)
I can find data through a simple search in digital environments (B)	30	26	31	23
I can perform clearly defined search for data and content (I)	20	18	20	13
I can adapt search strategies for most relevant results (S)	15	17	13	20
I can explain how to access the most relevant data (A)	20	21	20	24
I can create solutions for complex search problems (E)	15	16	16	20

B = Basic, I = Intermediate, S = Sufficient, A = Advanced, E = Expert

Table 4 Detailed results for "Evaluation of data and digital content" competence

Competence descriptor	Control group		Experimental group	
	Pre (%)	Post (%)	Pre (%)	Post (%)
I can identify the credibility of common data sources (B)	36	30	36	26
I can analyse clearly defined data and content (I)	16	14	17	14
I can compare and evaluate data sources (S)	15	17	14	16
I can assess the reliability of various data sources (A)	22	24	21	26
I can create solutions for complex evaluation problems (E)	11	15	12	18

B = Basic, I = Intermediate, S = Sufficient, A = Advanced, E = Expert

> *Programming the robot made everything click for me. When my code had an error, I could see exactly what went wrong—the robot turned too far or didn't stop. It's much easier to debug when you can see the problem physically happening. (Student E42)*
> *I never understood functions until we programmed the robotic arm. Creating a function to 'pick up an object' that we could reuse made perfect sense because I could see the arm doing the same movements each time we called it. (Student E78)*

4.2.2 Enhanced digital citizenship through IoT awareness

The substantial improvements in netiquette competencies (18% increase at advanced level for experimental group vs. 8% for control) initially surprised researchers. Analysis revealed that working with networked sensors and IoT devices naturally led to discussions about digital privacy, security, and ethical considerations that were more concrete than abstract online safety lessons.

A teacher explained:

> *When students built temperature sensors that uploaded data to the cloud, we naturally discussed who could access this data, what privacy meant for IoT devices, and the ethical considerations of automation. These concepts became real rather than theoretical. (Teacher E3)*

4.3 Detailed competence analysis by subdomain

Further analysis of the data collected through detailed self-assessments revealed nuanced differences in how STEM integration affected specific aspects of digital competence. Tables 3, 4, 5 and 6 present the percentage changes from pre- to post-assessment for specific competence descriptors.

The detailed analysis confirms that the experimental group's advantages were most pronounced in higher-order competencies, particularly in programming and digital citizenship domains.

Table 5 Detailed results for "Netiquette" competence

Competence descriptor	Control group		Experimental group	
	Pre (%)	Post (%)	Pre (%)	Post (%)
I can choose simple communication patterns (B)	30	20	30	15
I can express defined communication strategies (I)	17	14	16	10
I can discuss behavioural norms in digital environments (S)	17	22	18	20
I can apply cultural diversity awareness online (A)	16	24	15	33
I can integrate knowledge to guide others in netiquette (E)	20	20	21	22

B = Basic, I = Intermediate, S = Sufficient, A = Advanced, E = Expert

Table 6 Detailed results for "Programming" competence

Competence descriptor	Control group		Experimental group	
	Pre (%)	Post (%)	Pre (%)	Post (%)
I can list simple instructions for computer systems (B)	36	30	37	19.5
I can list defined instructions for routine tasks (I)	22	17.5	22.5	18.5
I can list instructions for specific problems (S)	18	21.5	18.5	21
I can determine appropriate instructions for tasks (A)	10	14	10	17
I can create solutions for complex programming problems (E)	14	17	12	24

B = Basic, I = Intermediate, S = Sufficient, A = Advanced, E = Expert

4.4 Teacher perspectives on STEM-enhanced UDL implementation

In-depth interviews with teachers revealed nuanced perspectives on how STEM content affected their ability to implement UDL principles. Table 7 presents the major themes organised by the research question.

Teachers consistently emphasised how STEM content naturally supported UDL implementation:

> *With traditional programming, I had to work hard to create multiple representations. With robotics, they're built in—students see the code, watch the robot move, hear the motors, feel the sensors. It's like UDL designs itself. (Teacher E5)*
> *However, teachers also identified unique challenges:The biggest challenge was the initial organisation. Managing physical components, ensuring equal access to materials, and maintaining equipment required new classroom management strategies. But once systems were in place, the benefits far outweighed the extra effort. (Teacher E11)*

4.5 Factors influencing implementation effectiveness

Analysis of implementation variations revealed several key factors that moderated the effectiveness of STEM-enhanced UDL, addressing RQ3.

4.5.1 Teacher factors

Teachers' prior experience with inclusive education and technical skills significantly influenced implementation quality. Figure 4 illustrates the relationship between teacher characteristics and implementation effectiveness.

Teachers with prior inclusive education experience showed higher implementation ratings in both groups. However, the effect was more pronounced in the experimental group, suggesting that STEM integration benefits teachers already familiar with differentiation strategies.

Table 7 Teacher perspectives on STEM-enhanced UDL implementation

Theme category	Specific theme	% of teachers
RQ1: How STEM enhances UDL implementation		
Representation	Physical demonstrations clarify abstract concepts	92%
	Sensor data provides real-time visual feedback	78%
	Multiple modalities naturally available	85%
Action/Expression	Students can build, not just code	88%
	Physical debugging is more intuitive	74%
	Portfolio options expand beyond digital	71%
Engagement	Real-world relevance increases motivation	96%
	Tangible outcomes sustain interest	89%
	Collaborative building enhances social learning	82%
RQ3: Implementation factors		
Facilitators	Prior maker space experience helps	68%
	Administrative support for materials	71%
	Student enthusiasm drives innovation	85%
Barriers	Initial setup time for physical materials	89%
	Storage and organization challenges	78%
	Need for specialized training	82%
	Safety considerations with electronics	64%
Adaptations	Simulation software when materials limited	75%
	Peer mentoring for technical skills	71%
	Modular kits for easier management	68%

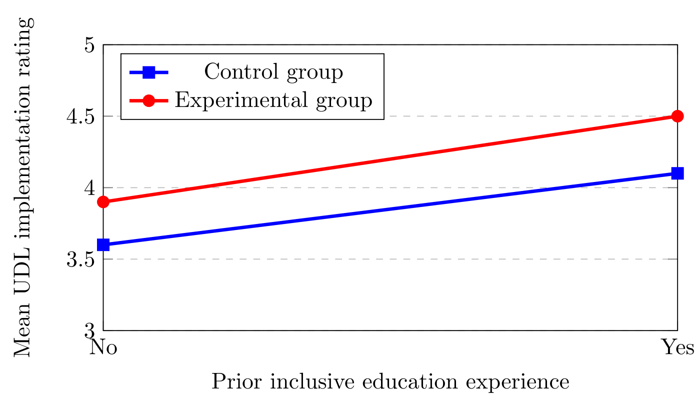

Fig. 4 UDL implementation ratings by teacher experience and group

4.5.2 Student factors

The impact of STEM-enhanced UDL varied by students' initial competence levels. Students in the lowest quartile showed the most dramatic improvements (32% reaching higher levels in experimental group vs. 11% in control group), while high-achieving students showed similar gains in both groups.

4.5.3 Content factors

Certain computer science topics proved more amenable to STEM enhancement than others. Topics with clear physical analogues (algorithms, data structures, control flow) showed the strongest benefits, while more abstract topics (database normalisation, network protocols) showed smaller differences between groups.

4.6 Synthesis of findings

The results provide strong support for our hypotheses:

H1 supported: STEM content significantly enhanced UDL implementation, particularly for principles requiring multiple representations and diverse action/expression options.

H2 supported: students receiving STEM-integrated UDL instruction showed significantly greater improvements in digital competence, with the largest effects in programming ($d = 0.82$) and digital citizenship ($d = 0.71$).

H3 partially supported: teacher and content factors significantly moderated implementation effectiveness, while school infrastructure factors showed less impact than anticipated, possibly due to the relatively homogeneous sample of western Ukrainian schools.

The convergence of quantitative and qualitative findings provides robust evidence that STEM content catalyses more effective UDL implementation in computer science education, with particular benefits for students who struggle with traditional abstract instruction.

5 Discussion

5.1 STEM content as a catalyst for enhanced UDL implementation

The findings of this study demonstrate that integrating STEM content into computer science education significantly enhances the implementation of UDL principles, confirming our theoretical model of STEM-UDL synergy. The experimental group's higher implementation ratings across key UDL principles–particularly equality and accessibility of use, flexibility of use, and accessibly presented information–reveal how physical computing and engineering design naturally expand the pedagogical possibilities for inclusive instruction.

This enhancement occurs through what we term "modal multiplication"—the expansion of available modalities for learning and expression that STEM content provides. Traditional computer science education, mainly confined to screen-based interactions, offers limited pathways for students to engage with and demonstrate an understanding of computational concepts. Integrating robotics, sensors, and physical computing fundamentally transforms this landscape by adding tactile, kinesthetic, and spatial dimensions to learning.

The significance of this modal multiplication extends beyond simply providing more options. As documented in our classroom observations, when students can see algorithms execute through robot movements, feel sensor responses, and physically construct computational systems, abstract concepts become concrete in ways that screen-based representations cannot achieve. This concretisation particularly benefits students who struggle with purely symbolic representations—a finding that aligns with cognitive load theory and embodied cognition research [40].

Our results extend previous findings by Schreffler et al. [19] on UDL in STEM contexts by demonstrating that the relationship between STEM and UDL is not merely additive but synergistic. While Schreffler et al. [19] showed that UDL principles can be successfully applied to STEM education, our study reveals that STEM content fundamentally enhances UDL principles' implementation. This distinction has important implications for curriculum design and pedagogical practice.

The teacher perspectives provide crucial insights into this synergy. Teacher E5 noted that with robotics, "it's like UDL designs itself"—a powerful observation that captures how STEM content naturally affords the multiple means of representation, action/expression, and engagement that UDL advocates. This natural affordance reduces the cognitive burden on teachers who might otherwise struggle to create diverse learning pathways, potentially explaining why teachers with prior inclusive education experience showed even greater implementation success in the experimental group.

However, our findings also reveal that this synergy is not automatic or without challenges. The implementation barriers identified–particularly around initial setup time, material management, and specialised training needs–highlight that realising the potential of STEM-enhanced UDL requires intentional design and support. These challenges echo findings from Wong [31] regarding STEM implementation complexity but add the additional layer of ensuring inclusive access to physical materials and spaces.

5.2 Differential impact on digital competence development

The substantially greater improvements in digital competence observed in the experimental group, particularly in programming and netiquette domains, provide empirical support for our hypothesis that STEM-integrated UDL instruction produces superior learning outcomes compared to traditional UDL instruction. The observed effect sizes ($d = 0.82$ for programming, $d = 0.71$ for netiquette) represent educationally significant improvements that warrant careful analysis.

The dramatic improvements in programming competence—with 12% of experimental group students reaching expert level compared to only 3% in the control group—can be understood through situated cognition theory. Students who program robots to navigate physical spaces or respond to environmental sensors engage in authentic problem-solving that mirrors real-world programming contexts. This authenticity accelerates skill development in ways that abstract exercises cannot match.

The qualitative data provides rich insights into the mechanisms underlying these improvements. Student E42's observation that "when my code had an error, I could see exactly what went wrong" highlights how physical computing transforms debugging from an abstract cognitive exercise into a concrete, observable process. This transformation is particularly significant given that debugging skills are often cited as a major barrier to programming proficiency [41].

The unexpected strength of netiquette and improvements in digital citizenship competencies reveal an important secondary benefit of STEM integration. As students work with networked sensors and IoT devices, concepts of privacy, security, and ethical technology use become tangible rather than theoretical [42]. This finding aligns with recent calls for more integrated approaches to digital citizenship education that move beyond rules-based instruction to experiential learning [43].

The pattern of results showing the greatest benefits for initially lower-performing students has profound equity implications. The 32% improvement rate for bottom-quartile students in the experimental group compared to 11% in the control group suggests that STEM-enhanced UDL may help close achievement gaps in computer science education. This finding is particularly significant given persistent concerns about equity in CS education and the need for approaches that support diverse learners [44].

5.3 Theoretical implications: reconceptualising the relationship between content and pedagogy

Our findings challenge the traditional separation of content and pedagogy in educational theory. While Shulman's influential framework of pedagogical content knowledge [45] treats content and pedagogy as distinct though related domains, our results suggest a more integrated relationship when considering inclusive education approaches.

In the context of UDL implementation, we find that content is not merely something to be made accessible through pedagogical techniques; instead, certain content–specifically STEM-integrated content–actively enables and enhances inclusive pedagogical practices. This finding suggests the need for what we term "pedagogically generative content"–curriculum content that inherently affords multiple pathways for learning and expression.

This reconceptualisation has important implications for how we think about curriculum design in inclusive education contexts. Rather than viewing UDL as a pedagogical overlay that can be applied to any content, our findings suggest that content selection should be guided by its potential to support diverse learners. STEM content, emphasising physical manipulation, real-world problem-solving, and multiple representations, emerges as particularly pedagogically generative.

Our empirical findings strongly support the theoretical model we proposed, in which STEM content and UDL principles exist in a mutually reinforcing relationship. This model contributes to the broader literature on educational innovation by demonstrating how curricular and pedagogical innovations can be designed to amplify each other's effects rather than simply coexist.

5.4 Practical implications for educational practice

The findings of this study have several immediate implications for educational practice, particularly relevant for educational systems undergoing reform or facing challenging circumstances.

5.4.1 Curriculum design implications

Our results suggest that computer science curricula should prioritise integrating physical computing and engineering design elements as both enrichment activities and core components that enable inclusive learning. The demonstrated benefits for diverse learners justify the additional resources and planning required for STEM integration.

Specific recommendations for curriculum designers include:

- Sequence topics to introduce physical computing early, allowing students to develop concrete understanding before moving to more abstract concepts
- Design units that naturally integrate multiple STEM disciplines rather than treating them as separate add-ons
- Include explicit connections between physical and digital representations in all programming units
- Develop assessment strategies that allow students to demonstrate competence through building and making, not just traditional coding

5.4.2 Teacher professional development

The critical role of teacher factors in implementation success highlights the need for comprehensive professional development that addresses both inclusive pedagogy and technical skills. Our findings suggest that professional development should:

- Integrate UDL principles with hands-on STEM activities rather than treating them separately
- Provide extensive practice with classroom management strategies for physical computing environments
- Include peer mentoring components, leveraging teachers with maker space experience
- Address safety considerations and material management explicitly

5.4.3 Resource allocation and infrastructure

While our study was conducted in schools with basic technological infrastructure, the findings have implications for resource allocation, even in constrained contexts. The demonstrated benefits justify investment in:

- Basic robotics kits and microcontroller boards that can be shared across classrooms
- Flexible furniture arrangements that support both computer work and physical construction
- Storage solutions for materials that ensure equitable access
- Professional development time for teachers to develop expertise

Importantly, our teachers' creative adaptations—such as using simulation software when physical materials were limited—demonstrate that STEM-enhanced UDL can be implemented even with constrained resources, though the full benefits require adequate material support.

5.5 Contextual considerations: implementing innovation in challenging circumstances

The Ukrainian context of this study—with ongoing war, damaged infrastructure, and massive educational disruption—provides important insights into implementing educational innovation under adverse conditions. Our findings demonstrate that pedagogical innovation is possible and perhaps even more critical in challenging circumstances.

The success of STEM-enhanced UDL in western Ukrainian schools, despite the broader national crisis, can be attributed to several factors that have relevance to other challenging contexts:

1. The tangible, hands-on nature of STEM activities appeared to provide psychological benefits beyond learning outcomes. Teachers reported that building and creating offered students a sense of agency and normalcy in an otherwise uncertain environment. This suggests that embodied learning approaches may have particular value in crisis contexts.
2. The flexibility inherent in UDL principles proved essential for accommodating the diverse needs of students affected by conflict–including internally displaced students, those dealing with trauma, and those with interrupted schooling. The multiple pathways for learning and expression allowed teachers to meet students where they were, both academically and emotionally.

3. The collaborative nature of many STEM activities fostered classroom community and peer support, which are critical factors in maintaining educational engagement during a crisis. While not a primary focus of our study, the social dimensions of learning emerged as an important secondary benefit.

These contextual insights align with Burde et al. [46] on education in emergencies, emphasising the importance of pedagogical approaches that address academic and psychosocial needs. Our findings extend this work by demonstrating how specific pedagogical innovations can serve these dual purposes.

5.6 Limitations and future research directions

While our study provides robust evidence for the benefits of STEM-enhanced UDL, several limitations must be acknowledged. While providing consistency for the quasi-experimental design, the geographic concentration in western Ukraine limits generalizability to regions more directly affected by conflict or with different infrastructure conditions. Future research should examine whether similar benefits can be achieved in more challenging contexts, including:

- Schools operating in hybrid or fully online modes due to security concerns
- Settings with more severe infrastructure limitations
- Contexts with different cultural attitudes toward hands-on learning

While the one-year implementation period is sufficient to demonstrate significant effects, it does not capture longer-term impacts or sustainability. Longitudinal research tracking students over multiple years would provide valuable insights into whether early exposure to STEM-enhanced UDL produces lasting benefits regarding computer science interest, persistence, and advanced skill development.

While aligned with Ukrainian educational priorities, our focus on digital competence as the primary outcome represents only one dimension of potential impact. Future research should examine broader outcomes, including:

- Development of general problem-solving and critical thinking skills
- Impact on self-efficacy and STEM identity formation
- Social-emotional learning outcomes
- Transfer of skills to other academic domains

The study's design, comparing STEM-enhanced UDL to traditional UDL rather than including non-UDL control conditions, was pragmatic given the Ukrainian educational context but limited our ability to decompose the separate contributions of STEM content and UDL principles. Future research employing factorial designs could better isolate these effects.

Methodologically, our reliance on teacher implementation of both conditions introduces potential variability that more standardised approaches might avoid. However, this ecological validity also represents a strength, as it demonstrates feasibility within real classroom contexts rather than under artificial experimental conditions.

5.7 Implications for global educational development

The success of STEM-enhanced UDL in the Ukrainian context has broader implications for global educational development, particularly for countries seeking to modernise their educational systems while ensuring inclusive access. Our findings suggest that the integration of STEM content and UDL principles offers a pathway for simultaneously addressing multiple educational priorities:

- Developing 21st-century skills essential for economic competitiveness
- Ensuring inclusive education that serves all learners
- Modernising pedagogical approaches beyond traditional transmission models
- Building resilience in educational systems facing various challenges

The model demonstrated in this study could be particularly valuable for countries undergoing educational reforms similar to Ukraine's New Ukrainian School initiative. By showing how curriculum content and inclusive pedagogy can mutually reinforce each other, our findings offer a template for reform efforts that avoid the false choice between excellence and equity.

Furthermore, the demonstrated benefits for students from diverse backgrounds and with varying initial skill levels suggest that STEM-enhanced UDL could help address persistent equity gaps in computer science education globally.

5.8 Conclusion of discussion

This study provides compelling evidence that STEM content catalyses more effective UDL implementation in computer science education, producing significant benefits for diverse learners. The synergy between STEM and UDL creates emergent properties neither approach can achieve independently, fundamentally transforming how students engage with and master computational concepts.

The implications extend beyond the specific context of Ukrainian computer science education to offer insights for global efforts to create more inclusive and effective STEM learning environments. When educational systems worldwide grapple with the dual challenges of developing digital competencies and ensuring equitable access to learning, the model of STEM-enhanced UDL offers a promising pathway forward. Despite significant challenges, the success achieved in Ukrainian schools provides hope and practical guidance for educators and policymakers committed to educational innovation that serves all learners.

6 Conclusion

This study investigated how integrating STEM content in computer science education enhances the implementation of UDL principles and its subsequent impact on students' digital competence development in Ukrainian secondary schools. Through a mixed-methods quasi-experimental design involving 28 teachers and 200 students, we examined whether STEM-oriented content–including robotics, physical computing, and engineering design–provides superior opportunities for implementing UDL principles compared to traditional computer science instruction.

Our findings provide strong empirical support for the theoretical model of STEM-UDL synergy. Integrating STEM content significantly enhanced the implementation of UDL principles, particularly those requiring multiple means of representation, action and expression, and engagement. Physical computing and robotics naturally provided additional modalities for learning that traditional screen-based instruction could not offer, creating what we term "modal multiplication"—an expansion of pathways through which students can engage with and demonstrate understanding of computational concepts.

The impact on student learning outcomes was substantial and educationally significant. Students in the STEM-integrated UDL group demonstrated markedly greater digital competence improvements than those receiving traditional UDL instruction. The most pronounced differences emerged in programming competencies, where 12% of experimental group students achieved expert-level proficiency compared to only 3% in the control group, and in digital citizenship, where understanding of privacy, security, and ethical technology use was enhanced through hands-on experience with networked devices and sensors.

Critically, the benefits were most pronounced for students with lower initial competency levels, suggesting that STEM-enhanced UDL may effectively address equity concerns in computer science education. The 32% improvement rate for bottom-quartile students in the experimental group, compared to 11% in the control group, indicates the potential of this approach to close achievement gaps while maintaining high standards for all learners.

The study also identified important implementation factors. Teacher characteristics significantly influenced implementation quality, particularly prior experience with inclusive education and technical skills. Content factors also played a role, with topics having clear physical analogues showing the strongest benefits. At the same time, implementation challenges existed–including initial setup time, material management, and training needs—and teachers developed creative adaptations that demonstrated the feasibility of this approach even in resource-constrained environments.

These findings have important theoretical implications, challenging traditional separations between content and pedagogy by demonstrating how certain content can be "pedagogically generative"–inherently affording multiple pathways for inclusive learning. This reconceptualisation suggests that curriculum design for inclusive education should prioritise content that naturally supports diverse learning needs rather than viewing inclusivity as a pedagogical overlay to be applied to any content.

The practical implications are equally significant. Educational systems seeking to modernise computer science education while ensuring inclusive access should prioritise integrating physical computing and engineering design as core components rather than enrichment activities. Teacher professional development must address both inclusive pedagogy and technical skills in integrated ways, and resource allocation should support the material requirements of hands-on STEM activities while recognising that creative adaptations can enable implementation even with constraints.

The Ukrainian context of this study—with ongoing war, infrastructure damage, and educational disruption–demonstrates that pedagogical innovation is not only possible but perhaps even more critical in challenging circumstances. The success achieved in western Ukrainian schools provides both inspiration and practical guidance for educational systems facing various challenges, from post-conflict recovery to rapid technological change.

Future research should extend these findings to more diverse contexts, examine longer-term impacts, and investigate broader outcomes beyond digital competence. The promising results from this initial study justify such expanded investigation and suggest the potential for STEM-enhanced UDL to transform computer science education globally.

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Author Contributions
O.V.B. developed the initial research plan, implemented the STEM-enhanced UDL intervention in experimental classrooms, collected data in schools in western Ukraine, and wrote sections on practical implementation. O.H.K. designed the research methodology, conducted statistical analyses of quantitative data, performed thematic analysis of qualitative data, and enhanced the results and discussion sections. S.O.S. developed the theoretical framework for STEM-UDL integration, strengthened the literature review, supervised the overall project, and led the manuscript writing and revision process. All authors participated in interpreting results, critically revising the manuscript, and approving the final version.

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Data Availability
The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request in the manuscript.

Declarations

Ethics approval and consent to participate
This research was conducted in accordance with ethical standards for educational research. The study was approved by the pedagogical councils of all participating institutions, and all necessary consents were obtained from participants and parents/guardians of minor participants.

Consent for publication
All participants provided informed consent to publish their anonymised data and responses. All authors have seen and approved the final version of the manuscript being submitted and give their consent for the article to be published in Discover Education.

Human ethics
The Ethical Council of Ternopil Volodymyr Hnatiuk National Pedagogical University approved the research. All data collection procedures were approved by the pedagogical councils of participating institutions. Participants were informed about the purpose of the study, the voluntary nature of participation, and confidentiality provisions.

Consent to participate
All participants provided informed consent to participate in this study. Additional parental consent was obtained for minor students.

Clinical trial number
Not applicable.

Competing interest
The authors declare no competing interest.

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