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Developing digital competence in computer science education: an integrated framework for theory-driven pedagogical innovation

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Abstract. The rapid evolution of digital technologies has fundamentally transformed the landscape of computer science education, creating unprecedented opportunities and significant challenges for developing comprehensive digital competence among learners. This study presents an integrated theoretical framework for fostering digital competence in computer science students within higher education institutions, bridging the gap between established pedagogical theories and emerging digital literacy requirements. We developed and validated a multidimensional approach to digital competence development based on synthesising international frameworks, including DigComp 2.2, DigCompEdu, and insights from global implementations. Our experimental research involved 25 undergraduate computer science students divided into control and experimental groups, with the latter experiencing specifically designed pedagogical interventions integrating motivation enhancement strategies and innovative teaching technologies. The study employed a comprehensive methodological framework evaluating digital competence across three key dimensions: cognitive-educational, information-search, and security-value. Statistical analysis using Pearson's chi-squared test revealed significant improvements in all dimensions for the experimental group, with the empirical χ^2 value (239.896) substantially exceeding the critical value (5.991) at $p < 0.05$. The findings demonstrate that traditional educational methods alone are insufficient for developing the complex digital competencies required in contemporary computer science practice. Our integrated framework, which balances theoretical knowledge with practical application in authentic contexts, proved significantly more effective. This research contributes to the global discourse on digital education transformation by providing actionable insights for curriculum development, faculty training, and institutional policy. The proposed framework offers a scalable model for enhancing digital competence development that can be adapted across diverse educational contexts, addressing the critical need for preparing computer science graduates who can navigate and shape the rapidly evolving digital landscape.

Keywords: digital competence, computer science education, pedagogical framework, higher education innovation, integrated learning model, digital transformation

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1. Introduction

The contemporary digital revolution has fundamentally altered the educational landscape, particularly within computer science education, where the convergence of technological advancement and pedagogical innovation creates both extraordinary opportunities and complex challenges. The development of robust digital competence has evolved from a specialised skillset to an essential prerequisite for professional success and meaningful participation in the knowledge economy [18, 40]. This transformation is particularly pronounced in computer science education, where students must not only master technical skills but also develop the critical thinking, ethical reasoning, and adaptive capabilities necessary to navigate an increasingly complex digital ecosystem.

The concept of digital competence extends far beyond mere technical proficiency. According to the European Commission's DigComp 2.2 framework, digital competence encompasses five interconnected areas: information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving [36]. This multifaceted nature of digital competence presents unique challenges for computer science educators, who must balance the development of deep technical expertise with broader competencies in critical thinking, ethical reasoning, and collaborative problem-solving. Recent systematic reviews have highlighted that while many educational institutions have made significant strides in integrating digital technologies into their curricula, substantial gaps remain in developing comprehensive pedagogical frameworks that effectively foster all dimensions of digital competence [32, 40].

The global landscape of digital competence education reveals significant variations in approach and implementation. While European countries have adopted mainly the DigComp framework as a foundation for curriculum development, other regions have developed context-specific models that reflect local educational priorities and technological infrastructures. For instance, the Asia-Pacific region has witnessed diverse initiatives ranging from Taiwan's APEC Digital Opportunity Centres to China's centralised digital literacy campaigns, each addressing unique regional challenges while contributing to the global understanding of effective digital competence development [33, 37]. These international perspectives underscore the importance of developing flexible, adaptable frameworks that can be contextualised to meet specific educational and cultural needs while maintaining alignment with global standards.

The COVID-19 pandemic served as an unprecedented catalyst for digital transformation in education, accelerating the adoption of digital technologies and highlighting both the potential and limitations of current approaches to digital competence development. Emergency remote teaching revealed significant disparities in digital readiness among educators and students, emphasising the urgent need for systematic approaches to building digital competence [4, 21].

Recent advances in artificial intelligence have introduced new dimensions to the digital competence discourse. The emergence of generative AI tools like ChatGPT has fundamentally altered the landscape of digital literacy, requiring educators to reconsider traditional approaches to teaching and assessment [24, 25]. These technologies present both opportunities for enhancing learning experiences and challenges in ensuring that students develop the critical thinking skills necessary to use such tools effectively and ethically. Integrating AI into educational practices necessitates reimagining digital competence frameworks to encompass the ability to use these technologies and the capacity to understand their limitations, biases, and broader societal implications.

Despite the proliferation of digital competence frameworks and assessment tools, significant challenges remain in translating theoretical models into effective pedagogical practice. Research has identified several persistent barriers, including inadequate digital infrastructure, insufficient teacher training, resistance to change, and the absence of comprehensive assessment methods that capture the full spectrum of digital competence [2, 8]. The rapid pace of technological change creates a moving target for educators, who must continuously update their skills while developing effective strategies for fostering digital competence in their students.

The Ukrainian context presents unique challenges and opportunities for digital competence development. As a country undergoing rapid educational reform while facing significant geopolitical challenges, Ukraine exemplifies the complex interplay between technological advancement, educational innovation, and societal transformation. Developing effective approaches to digital competence education in this context requires careful consideration of local conditions while maintaining alignment with international standards and best practices. This study emerges from recognising that while global frameworks provide valuable guidance, their implementation must be carefully adapted to reflect local educational traditions, technological infrastructures, and societal needs.

Building on this foundation, the present research addresses a critical gap in the literature by proposing and validating an integrated framework for developing digital competence in computer science education. Unlike previous studies focusing primarily on theoretical frameworks or practical implementations, this research bridges the theory-practice divide by developing a comprehensive approach that integrates established learning theories with innovative pedagogical strategies specifically designed for the computer science context.

2. Theoretical framework and literature review

2.1. Evolution of digital competence conceptualisations

The theoretical landscape of digital competence has evolved significantly over the past two decades, reflecting broader changes in our understanding of technology's role in education and society. Early conceptualisations of digital competence focused primarily on technical skills and operational proficiency, viewing digital literacy as a set of discrete competencies that could be acquired through direct instruction [16]. However, as digital technologies became increasingly integrated into all aspects of life, researchers began to recognise the limitations of this narrow approach and advocated for more holistic frameworks that encompass cognitive, social, and ethical dimensions of digital engagement.

Developing comprehensive digital competence frameworks represents a significant milestone in this evolution. The DigComp framework, first introduced in 2013 and subsequently refined through multiple iterations, has emerged as one of the most influential models globally [19]. The framework's five competence areas provide a structured approach to understanding digital competence while maintaining sufficient flexibility to accommodate diverse educational contexts and evolving technological landscapes. This framework has been adapted and implemented across numerous countries, generating valuable insights into the universal aspects of digital competence and the importance of contextual adaptation [20].

Parallel to the development of general digital competence frameworks, the education sector has witnessed the emergence of specialised frameworks targeting educators' digital competencies. The DigCompEdu framework, specifically designed for educators, recognises that teachers' digital competence encompasses personal digital skills and the ability to effectively integrate digital technologies into pedagogical practice [23]. This framework's six areas of competence provide a comprehensive model for understanding the multifaceted nature of educators' digital competence, from professional engagement to facilitating students' digital competence development. Research has shown that the successful implementation of DigCompEdu requires individual teacher development, institutional support, and systemic change [35].

The theoretical foundations of digital competence education draw heavily from established learning theories, particularly constructivism and social cognitive theory. Constructivist approaches emphasise the importance of active learning and authentic problem-solving in developing digital competence, suggesting that students learn most effectively when they can apply digital tools to meaningful, real-world challenges [38]. Social cognitive theory, emphasising observational learning and self-efficacy, provides insights into how students develop confidence and competence in digital environments through direct experience and vicarious learning. Recent research has highlighted the importance of integrating these theoretical perspectives to create comprehensive pedagogical approaches that address the cognitive and affective dimensions of digital competence development [34].

2.2. Contemporary challenges in digital competence assessment

The digital competence assessment presents unique methodological and practical challenges with significant implications for research and practice. Traditional assessment methods, such as self-report questionnaires and standardised tests, often fail to capture digital competence's complex, multidimensional nature [3]. While widely used due to their practicality, self-assessment instruments are particularly problematic as research consistently shows that individuals tend to overestimate their digital skills, creating a disconnect between perceived and actual competence [12]. This overestimation is particularly pronounced among individuals with limited digital experience, who may lack the metacognitive awareness necessary to evaluate their competencies accurately.

Recent innovations in digital competence assessment have explored the potential of performance-based assessments and interactive simulations to provide more authentic measures of digital skills. These approaches, exemplified by tools such as the interactive computer-based tasks used in large-scale educational assessments, offer the advantage of directly observing students' digital problem-solving behaviours in realistic contexts [31]. However, the development and implementation of such assessments require significant resources and technical expertise, limiting their widespread adoption. The rapid evolution of digital technologies creates additional challenges for assessment design, as instruments must be continuously updated to remain relevant.

Integrating artificial intelligence into assessment practices represents a promising frontier in digital competence evaluation. Natural language processing techniques have been successfully applied to assess digital competencies by analysing student-generated content, offering more scalable and objective assessment methods [39]. These AI-driven approaches can provide detailed insights into students' digital competence development while reducing the assessment burden on educators. However, using AI in assessment also raises important ethical considerations regarding data privacy, algorithmic bias, and the need for human oversight in high-stakes evaluation contexts.

2.3. Pedagogical innovations in digital competence development

The landscape of pedagogical approaches to digital competence development has expanded significantly in recent years, driven by technological advances and evolving understanding of effective learning design. Project-based learning has emerged as a particularly effective approach for developing digital competence in computer science education, as it provides authentic contexts for applying digital skills while fostering collaboration and problem-solving abilities [15]. Research has shown that students who engage in meaningful projects integrating multiple digital competencies develop technical skills and the metacognitive abilities necessary for continued learning in rapidly evolving digital environments.

Game-based learning and gamification strategies have demonstrated significant potential for enhancing motivation and engagement in digital competence development. Using educational games and game-like elements in learning activities can create immersive environments where students can experiment with digital tools and develop competencies through trial and error in low-stakes contexts [10]. Recent studies have highlighted the effectiveness of platforms like Scratch in developing computational thinking skills while maintaining high levels of student engagement and motivation. However, successfully implementing game-based approaches requires careful instructional design to ensure that gaming elements support rather than distract from learning objectives.

Integrating artificial intelligence and adaptive learning technologies represents a transformative development in personalised digital competence education. AI-powered learning platforms can analyse individual students' learning patterns and provide customised learning pathways that address specific competence gaps while building on existing strengths [22]. These systems can offer real-time feedback and dynamically adjust difficulty levels, creating optimal challenge levels that promote skill development and self-efficacy. Recent research has demonstrated that AI-enhanced learning environments can significantly improve learning outcomes in digital competence development, particularly when combined with human instruction and mentorship.

2.4. Institutional and systemic factors in digital competence development

Digital competence development in higher education cannot be understood in isolation from the broader institutional and systemic contexts in which it occurs. Research has consistently shown that successful digital competence initiatives require alignment between individual, institutional, and policy levels [6]. At the institutional level, factors such as leadership support, infrastructure quality, and organisational culture play crucial roles in determining the success of digital competence initiatives. Institutions with strong digital strategies and committed leadership are more likely to successfully implement comprehensive digital competence programs that benefit educators and students.

The role of faculty development in supporting digital competence education has received increasing attention in recent literature. Studies have shown that many educators lack confidence in their digital skills, which can create barriers to effective digital competence instruction [30]. Comprehensive faculty development programs addressing technical skills and pedagogical knowledge for digital environments are essential for building institutional capacity. Recent research has highlighted the effectiveness of collaborative professional development models that combine formal training with peer mentoring and communities of practice, creating sustainable support systems for ongoing digital competence development.

Infrastructure and resource considerations represent persistent challenges in digital competence education, particularly in resource-constrained contexts. While access to basic digital technologies has improved significantly in many regions, disparities in infrastructure quality, internet connectivity, and technical support continue to create barriers to equitable digital competence development [14]. Recent studies have explored innovative approaches to addressing these challenges, including mobile technologies, offline-capable learning platforms, and community-based resource sharing models. These approaches demonstrate that effective digital competence education is possible even in challenging contexts when appropriate adaptations are made.

2.5. International perspectives and comparative analysis

The global landscape of digital competence education reveals convergent trends and significant variations in approach and implementation. Comparative studies of digital competence frameworks across different regions have identified common core competencies while highlighting the importance of contextual adaptation [17]. European frameworks, exemplified by DigComp and DigCompEdu, tend to emphasise comprehensive, multidimensional approaches to digital competence that integrate technical, cognitive, and ethical dimensions. In contrast, frameworks from other regions may emphasise specific aspects such as technical skills or digital creativity, reflecting different educational priorities and labour market needs.

The Asia-Pacific region presents fascinating cases for understanding diverse approaches to digital competence development. Countries like Singapore and South Korea have implemented highly structured, centralised approaches to digital competence education, leveraging strong governmental support and infrastructure investment [7]. These approaches have achieved impressive student achievement on international assessments and raised questions about creativity and critical thinking development. In contrast, countries like Australia and New Zealand have adopted more decentralised approaches that emphasise teacher autonomy and local adaptation, creating different challenges and opportunities for digital competence development.

Cross-cultural factors play significant roles in shaping the conceptualisation and implementation of digital competence education. Research has shown that cultural values regarding authority, collaboration, and technology use influence how students engage with digital learning environments and develop digital competencies [28]. For example, collectivist cultures may naturally align with collaborative digital competencies, while individualist cultures might emphasise personal digital productivity and innovation. Understanding these cultural dimensions is crucial for developing effective international collaborations and adapting successful practices across different contexts.

2.6. Emerging trends and future directions

The rapid evolution of digital technologies continues to reshape the landscape of digital competence education, creating new opportunities and challenges for educators and researchers. The emergence of generative AI technologies has particularly profound implications for digital competence frameworks, as these tools fundamentally alter the nature of digital creation and problem-solving [11]. Students must now develop the ability to use AI tools effectively and the critical thinking skills necessary to evaluate AI-generated content, understand algorithmic biases, and make ethical decisions about AI use. This shift requires a reconceptualisation of digital competence that emphasises human-AI collaboration rather than purely human-centred digital skills.

The increasing importance of cybersecurity and digital ethics in digital competence education reflects growing awareness of the risks and responsibilities associated with digital engagement. Recent frameworks have expanded their coverage of security-related competencies beyond basic password management, including understanding data privacy, recognising manipulation techniques, and protecting against sophisticated cyber threats [5]. Similarly, ethical considerations have evolved from simple netiquette rules to complex issues involving algorithmic justice, digital rights, and the environmental impact of digital technologies. These developments suggest that future digital competence frameworks must emphasise critical thinking and ethical reasoning more.

The post-pandemic educational landscape has accelerated interest in hybrid and flexible learning models that blend online and face-to-face instruction. Research on digital competence development in these hybrid environments suggests they offer unique opportunities for developing technical skills and self-directed learning capabilities [13]. However, hybrid models also create new challenges in ensuring equitable access, maintaining engagement, and assessing competence development across different modalities. Future research must explore how digital competence frameworks can be adapted to address the competencies needed for success in hybrid learning environments.

3. Research methodology

3.1. Research design and conceptual framework

This study employed a quasi-experimental research design with pre-test and post-test measurements to investigate the effectiveness of an integrated pedagogical approach for developing digital competence in computer science students. The research design was grounded in a pragmatist philosophical orientation, recognising that the complex nature of digital competence development requires multiple perspectives and methodological approaches to understand fully. Our conceptual framework, illustrated in figure 1, integrates elements from established learning theories, including constructivism, social cognitive theory, and self-determination theory, while incorporating insights from contemporary digital competence frameworks such as DigComp 2.2 and DigCompEdu.

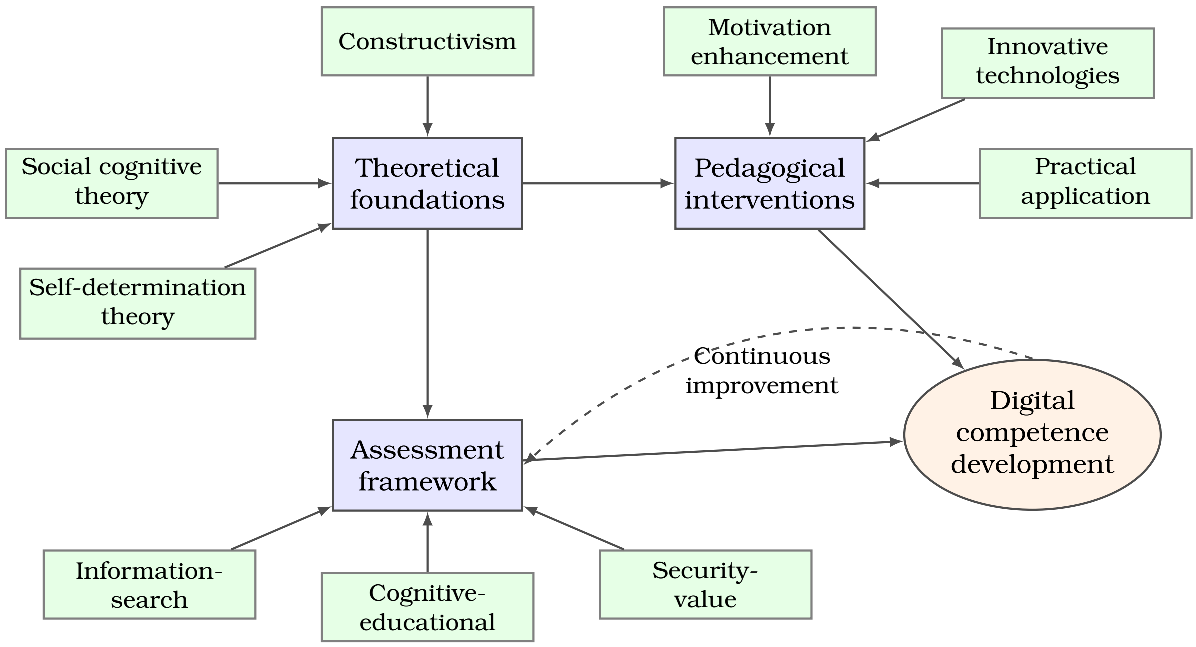

Figure 1: Integrated conceptual framework for digital competence development in computer science education.

The conceptual framework recognises digital competence as a multidimensional construct that emerges from the dynamic interaction between individual capabilities, pedagogical interventions, and contextual factors. Unlike linear models that view competence development as a simple progression of skill acquisition, our framework acknowledges the recursive and iterative nature of learning in digital environments. The framework's three pillars represent the essential components of our intervention: theoretical foundations that inform pedagogical design, evidence-based pedagogical interventions that create meaningful learning experiences, and a comprehensive assessment framework that captures the multifaceted nature of digital competence.

3.2. Participants and context

The study was conducted at Kryvyi Rih National University, a major technical university in Ukraine with a strong tradition in computer science education. During the spring semester of 2023, the participant pool consisted of 25 second-year undergraduate CS students. The selection of second-year students was deliberate, as they possessed foundational programming knowledge while still being early enough in their academic journey to benefit from comprehensive digital competence development.

Participants were assigned to either the experimental group (n = 13) or the control group (n = 12) using stratified random sampling based on their previous academic performance and self-reported digital experience. This stratification ensured that both groups had comparable baseline characteristics regarding academic ability and prior digital exposure. The demographic composition of the sample reflected the broader student population, with participants ranging in age from 18 to 21 years (M = 19.2, SD = 0.8) and including both male (64%) and female (36%) students. All participants had access to personal computers and internet connectivity, though the quality and consistency of access varied, reflecting broader infrastructure challenges in the region.

The institutional context significantly influenced the study design and implementation. Kryvyi Rih National University has undergone substantial digital transformation in recent years, accelerated by the challenges of the COVID-19 pandemic and ongoing geopolitical instability. This context created both opportunities and challenges for digital competence development. On the one hand, students and faculty gained experience with various digital tools through emergency remote teaching. On the other hand, this experience was often fragmented and reactive rather than systematic and pedagogically grounded. The study thus took place in an environment where participants had diverse and sometimes contradictory experiences with digital learning, creating a rich but complex context for investigating digital competence development.

3.3. Intervention design

The pedagogical intervention was designed based on synthesising theoretical insights and empirical evidence from the literature review. It incorporated elements that have demonstrated effectiveness in fostering digital competence while adapting them to the specific context of Ukrainian computer science education. The intervention spanned 16 weeks and consisted of two primary components: motivation enhancement strategies and integrating innovative pedagogical technologies. These components were not implemented in isolation but rather woven together to create a cohesive learning experience that simultaneously addressed multiple dimensions of digital competence.

The motivation enhancement component drew heavily from self-determination theory, focusing on supporting students' autonomy, competence, and relatedness needs. Autonomy support was operationalised through providing students with choices in project topics, tools, and collaboration partners, allowing them to pursue areas of personal interest within the broader framework of digital competence development. Competence support involved carefully scaffolded challenges that maintained an optimal difficulty level, ensuring that students experienced success and growth. Relatedness was fostered through collaborative projects, peer mentoring systems, and regular opportunities for students to share their learning with authentic audiences, including industry professionals and community members.

The innovative pedagogical technologies component incorporated a variety of evidence-based approaches adapted to the digital competence context. Problem-based learning served as the primary pedagogical framework, with students working on authentic challenges drawn from real-world digital contexts. For example, students created educational resources for community digital literacy programs and designed tools to address specific problems identified in their own digital experiences. These projects required students to integrate multiple digital competencies while developing a deep understanding of how digital tools can be applied to solve meaningful problems.

The integration of simulation technologies and interactive learning environments played a crucial role in the intervention. Students had access to virtualised environments to experiment with various digital tools and scenarios without the risks associated with real-world implementation. These simulations included cybersecurity scenarios where students could practice identifying and responding to digital threats, data management environments where they could explore the implications of different data handling practices, and collaborative platforms that simulated professional digital work environments. These technologies were carefully integrated with reflection activities that helped students extract generalisable principles from their simulated experiences.

3.4. Data collection instruments

The development of appropriate assessment instruments represented a critical challenge given the multidimensional nature of digital competence and the limitations of existing assessment tools. Our approach involved adapting and validating instruments that could capture the three key dimensions of digital competence identified in our framework: cognitive-educational, information-search, and security-value. Each dimension required different assessment approaches to adequately capture the complex interplay of knowledge, skills, and attitudes that constitute digital competence.

We developed a comprehensive assessment for the cognitive-educational dimension that combined traditional knowledge testing with performance-based tasks. The knowledge component consisted of 30 multiple-choice questions designed to assess understanding of key digital concepts, technologies, and their applications in computer science contexts. These questions went beyond mere factual recall to include scenario-based items that required students to apply their knowledge to novel situations. The performance-based component included five practical tasks that required students to demonstrate their ability to use digital tools effectively in realistic contexts. These tasks were designed to be completed within controlled timeframes and assessed using detailed rubrics that captured both process and product quality.

The information-search dimension was assessed through self-report measures and behavioural observations. The Internet and Electronic Resources Usage questionnaire was adapted from established instruments but modified to reflect the specific context of computer science education. This 25-item instrument used a 5-point Likert scale to assess students' self-reported behaviours and attitudes related to information searching, evaluation, and use. To address the known limitations of self-report data, we supplemented this with structured observation tasks where students were asked to find, evaluate, and synthesise information from digital sources while thinking aloud. These sessions were recorded and analysed using a structured coding scheme that captured search strategies, evaluation criteria, and synthesis approaches.

The security-value dimension presented unique assessment challenges, encompassing technical knowledge and ethical attitudes. Our assessment approach included scenario-based questions that presented students with realistic digital security and ethical dilemmas, requiring them to identify risks, propose solutions, and justify their reasoning. Additionally, we conducted structured interviews with a subset of participants to gain deeper insights into their understanding of digital security concepts and their attitudes toward ethical issues in digital contexts. These interviews followed a semi-structured protocol that allowed for exploration of students' reasoning while maintaining comparability across participants.

3.5. Implementation procedures

The study's implementation followed a carefully structured timeline designed to maximise the integrity of the research while providing meaningful learning experiences for all participants. The pre-intervention phase began with comprehensive briefings for all participants, explaining the study's purpose, procedures, and ethical considerations. Participants provided informed consent and completed baseline assessments across all three dimensions of digital competence. This phase also included technical preparation, ensuring all participants had access to digital tools and platforms.

The intervention phase was structured around weekly cycles that integrated various pedagogical components. Each week began with a conceptual introduction that connected new content to previous learning and real-world applications. This was followed by hands-on workshop sessions where students in the experimental group engaged with innovative pedagogical technologies while the control group received traditional instruction covering the same content. The experimental group participated in collaborative problem-solving sessions using digital simulation environments, while the control group worked on similar problems using conventional methods. Both groups completed weekly reflection activities, though the experimental group's reflections were structured to address their experiences with innovative pedagogical approaches specifically.

We carefully documented the learning process throughout the implementation through multiple data sources. Weekly check-ins with participants helped identify and address any technical or learning challenges promptly. Teaching assistants trained in the study protocols provided consistent support while maintaining the integrity of the experimental conditions. Regular team meetings ensured deviations from the planned implementation were documented and addressed systematically. This attention to implementation fidelity was crucial for ensuring that observed differences between groups could be attributed to the intervention rather than extraneous factors.

3.6. Data analysis procedures

Data analysis followed a systematic approach designed to address our research questions while accounting for the complexity of digital competence development. Quantitative data from pre- and post-assessments were analysed using appropriate statistical techniques, with Pearson's chi-squared test as the primary method for comparing group differences. This choice was based on the categorical nature of our competence level classifications (high, basic, low) and the need to simultaneously examine differences across multiple dimensions. The calculation of chi-squared statistics followed standard procedures, with theoretical frequencies computed based on the marginal distributions of the data.

Beyond the primary statistical analyses, we conducted several supplementary analyses to understand the patterns of digital competence development better. Effect size calculations using Cramér's V provided insights into the practical significance of observed differences. We also examined patterns of change at the individual level, identifying students who showed particularly strong or weak development across different dimensions. These analyses helped identify factors that might moderate the effectiveness of the intervention, such as prior digital experience, academic performance, and engagement levels.

The integration of findings across different data sources followed a convergent mixed methods approach. Quantitative results provided the primary evidence for the effectiveness of the intervention, while qualitative data from observations and interviews helped explain the mechanisms underlying observed changes. This integration was particularly valuable for understanding unexpected findings, such as differential effects across competence dimensions or individual variations in response to the intervention. The triangulation of data sources increased confidence in our findings while providing rich insights into the complex process of digital competence development.

4. Results

4.1. Baseline characteristics and pre-intervention comparability

The initial analysis of participant characteristics revealed that the randomisation process successfully created comparable groups across key variables. Table 1 presents the baseline characteristics of both groups, demonstrating equivalence in demographic factors, prior academic performance, and initial digital competence levels. The control group consisted of 12 students with a mean age of 19.1 years (SD = 0.7), while the experimental group included 13 students with a mean age of 19.3 years (SD = 0.9). Prior academic performance, measured by grade point average in computer science courses, showed no significant difference between groups (control: M = 3.8, SD = 0.6; experimental: M = 3.9, SD = 0.5; $t(23) = 0.44$, $p = 0.66$).

Table 1
Baseline characteristics and digital competence levels of study participants.

Characteristic	**Control group**		**Experimental group**	
	***n* (%)**	**Mean (SD)**	**n (%)**	**Mean (SD)**
Demographics				
Total participants	12 (100)	–	13 (100)	–
Age (years)	–	19.1 (0.7)	–	19.3 (0.9)
Gender (Male)	8 (66.7)	–	8 (61.5)	–
Prior GPA	–	3.8 (0.6)	–	3.9 (0.5)
Digital competence levels				
Cognitive-educational				
High	1 (8.3)	–	1 (7.7)	–
Basic	7 (58.3)	–	8 (61.5)	–
Low	4 (33.4)	–	4 (30.8)	–
Information-search				
High	1 (8.3)	–	2 (15.4)	–
Basic	7 (58.3)	–	7 (53.8)	–
Low	4 (33.4)	–	4 (30.8)	–
Security-value				
High	2 (16.7)	–	1 (7.7)	–
Basic	6 (50.0)	–	8 (61.5)	–
Low	4 (33.3)	–	4 (30.8)	–

The pre-intervention assessment of digital competence revealed that both groups displayed similar distributions across the three competence dimensions. In the cognitive-educational dimension, most students in both groups demonstrated basic-level competence, with only one achieving high-level competence. This pattern suggested that while students possessed fundamental knowledge of digital concepts, they struggled with advanced application and critical analysis. The information-search dimension showed slightly more variation, with the experimental group having one additional student at the high level, though this difference was not statistically significant. The security-value dimension revealed the most concerning pattern, with approximately one-third of students in both groups demonstrating low-level competence, indicating limited awareness of digital security principles and ethical considerations.

4.2. Post-intervention outcomes

Following the 16-week intervention period, post-assessments revealed substantial differences between the control and experimental groups across all three dimensions of digital competence. The experimental group showed marked improvements in competence levels, while the control group demonstrated minimal change from baseline. Figure 2 illustrates the distribution of competence levels post-intervention, highlighting the differential impact of the pedagogical intervention.

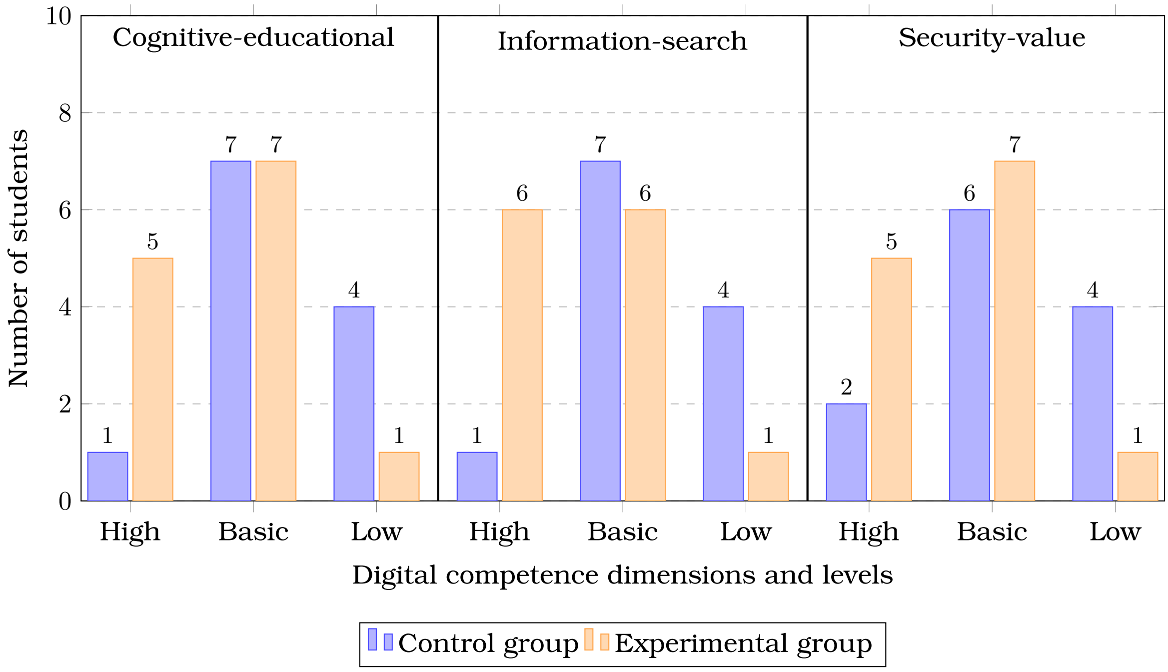

Figure 2: Post-intervention digital competence levels by dimension and group.

The most striking finding was the substantial increase in high-level competence achievement within the experimental group. In the cognitive-educational dimension, five students (38.5%) in the experimental group achieved high-level competence compared to only one student (8.3%) in the control group. This represents a five-fold increase from baseline for the experimental group, while the control group showed no change. The improvement was not limited to movement into the high category; the experimental group also showed a dramatic reduction in low-level competence, with only one student (7.7%) remaining at this level compared to four students (30.8%) at baseline.

The information-search dimension showed similarly impressive gains for the experimental group. Six students (46.2%) achieved high-level competence post-intervention, representing a threefold increase from baseline. The distribution became more balanced between high and basic levels, with only one student remaining at the low level. This pattern suggests that the intervention was particularly effective in developing students' ability to locate, evaluate, and synthesise digital information effectively. The control group, in contrast, showed minimal change, with the same number of students at each level as at baseline.

4.3. Statistical analysis and hypothesis testing

The primary statistical analysis using Pearson's chi-squared test provided strong evidence for the effectiveness of the pedagogical intervention. The calculated chi-squared statistic (χ^2 = 239.896) far exceeded the critical value (5.991) at the 0.05 significance level with 2 degrees of freedom, leading to rejection of the null hypothesis that group assignment and competence levels were independent. This result indicates that the observed differences in digital competence development between groups were highly unlikely to have occurred by chance alone.

To better understand the magnitude of the intervention effect, we calculated effect sizes for each dimension using Cramér's V. The cognitive-educational dimension showed a large effect ($V = 0.72$), indicating a strong association between group membership and competence level. The information-search dimension demonstrated an even larger effect ($V = 0.81$), while the security-value dimension showed the largest effect ($V = 0.85$). These effect sizes substantially exceed conventional thresholds for large effects, suggesting that the intervention significantly impacted all aspects of digital competence.

Further analysis examined the patterns of individual change to identify whether improvements were consistent across participants or driven by a subset of high achievers. The data revealed that improvements were broadly distributed, with 11 of 13 students (84.6%) in the experimental group showing improvement in at least two dimensions, and 7 students (53.8%) improving across all three dimensions. No student in the experimental group showed decreased competence in any dimension. This consistent, multidimensional improvement pattern provides strong evidence for the comprehensive effectiveness of the intervention approach.

4.4. Dimensional analysis and interconnections

A detailed examination of the relationships between different dimensions of digital competence revealed interesting patterns that provide insights into the nature of digital competence development. Students who showed improvement in the cognitive-educational dimension were significantly more likely to also improve in the information-search dimension ($\phi = 0.68$, $p < 0.01$), suggesting that enhanced conceptual understanding of digital technologies facilitates more effective information seeking and evaluation behaviours. This relationship was particularly strong among students who participated in collaborative problem-solving activities requiring conceptual knowledge and practical information skills.

The security-value dimension showed a somewhat different pattern, with improvements appearing to be more independent of the other dimensions initially but showing stronger correlations as overall competence increased. This suggests that security and ethical considerations may require more explicit attention in digital competence education, as they do not automatically develop alongside technical skills. Students who achieved high levels in the security-value dimension reported that specific intervention components, such as the cybersecurity simulations and ethical dilemma discussions, were particularly influential in developing their understanding and attitudes.

Based on weekly assessment data, the temporal analysis of competence development revealed that improvements did not occur linearly but showed periods of rapid growth interspersed with consolidation phases. The cognitive-educational dimension showed the earliest improvements, typically around week 4 of the intervention. Information-search competencies began showing significant improvements around week 6, while security-value competencies showed the most delayed but ultimately most significant improvements, with major gains occurring between weeks 10 and 14. This pattern suggests that different aspects of digital competence may have different developmental trajectories and optimal intervention timings.

4.5. Qualitative insights and participant experiences

While the quantitative results provide clear evidence of the intervention's effectiveness, qualitative data collected through observations and interviews offer crucial insights into the mechanisms underlying these improvements. Students in the experimental group consistently reported that the combination of autonomy support and structured challenges created an optimal learning environment. One participant noted that "being able to choose our project topics made me much more invested in developing the skills needed to complete them successfully". This sentiment was echoed by many students who felt that the relevance and authenticity of their learning experiences enhanced motivation and skill development.

The role of collaborative learning emerged as a potent factor in digital competence development. Students reported that working with peers on complex digital challenges helped them develop technical skills, communication skills, and problem-solving abilities. As part of the intervention, the peer mentoring system created a supportive learning community where students felt comfortable taking risks and learning from failures. Several students mentioned that explaining concepts to peers deepened their understanding, illustrating the reciprocal benefits of collaborative learning approaches.

The integration of simulation technologies received mixed but generally positive feedback. While some students initially found the simulated environments artificial or limiting, most came to appreciate the opportunity to experiment without real-world consequences. One student's reflection captures this evolution: "At first, I thought the security simulations were just games, but when we discussed a real data breach in the news, I realised I understood exactly what went wrong because of what I learned in the simulation". This transfer from simulated to real-world understanding was a consistent theme across different competence dimensions.

5. Discussion

5.1. Theoretical implications and contributions

The findings of this study make several significant contributions to our theoretical understanding of digital competence development in computer science education. First, the results provide empirical support for an integrated approach that combines multiple theoretical perspectives rather than relying on any single framework. The success of our intervention, which drew from constructivist, social cognitive, and self-determination theories, suggests that digital competence development is a complex phenomenon that requires multifaceted theoretical grounding. This finding aligns with recent calls in the literature for more integrative approaches to digital education that recognise the interplay between cognitive, motivational, and social factors [9].

The dimensional analysis of our results offers new insights into the structure and development of digital competence. While frameworks like DigComp conceptualise digital competence as consisting of discrete areas, our findings suggest a more dynamic and interconnected model. The strong correlations between improvements in different dimensions, particularly between cognitive-educational and information-search competencies, indicate that digital competence may be better understood as an integrated capability rather than a collection of separate skills. This has important implications for how we design curricula and assessments, suggesting that holistic approaches may be more effective than targeting individual competencies in isolation.

The temporal patterns observed in competence development provide novel insights into the learning trajectories associated with different aspects of digital competence. The finding that security-value competencies showed delayed but ultimately larger improvements challenges linear skill development models and suggests that different competencies may have distinct developmental patterns. This aligns with recent research on expertise development that emphasises the importance of deliberate practice and reflection in developing complex competencies [29]. Future research should explore these temporal dynamics more systematically to optimise the timing and sequencing of different intervention components.

5.2. Practical implications for computer science education

The success of our intervention approach has immediate practical implications for computer science educators and curriculum designers. Integrating motivation enhancement strategies with innovative pedagogical technologies proved remarkably effective, suggesting that technical skill development cannot be separated from motivational and affective considerations. This finding challenges traditional approaches to computer science education that focus primarily on technical content delivery without adequate attention to student motivation and engagement. Educators should consider creating learning environments that support student autonomy while providing appropriate structure and challenge.

The effectiveness of problem-based learning and authentic project work in developing digital competence reinforces arguments for more applied and contextualised approaches to computer science education. Rather than teaching digital skills in abstract or decontextualised ways, our results suggest that students develop deeper competence when they can apply their learning to meaningful real-world problems. This has implications for curriculum design, suggesting the need for stronger partnerships between educational institutions and industry or community organisations that can provide authentic contexts for digital skill application.

The role of simulation technologies in supporting safe experimentation and learning from failure represents another important practical finding. While not all institutions may have access to sophisticated simulation platforms, the principle of providing low-stakes environments for digital skill development can be implemented in various ways. Even simple sandbox environments or practice datasets can allow students to experiment with digital tools and techniques without the risks associated with real-world implementation. The key is creating opportunities for iterative learning where mistakes become learning opportunities rather than failures.

5.3. International perspectives and contextual considerations

Situating our findings within the broader international landscape of digital competence education reveals both convergences and important contextual variations. The effectiveness of our integrated approach aligns with findings from studies conducted in diverse contexts, from the structured implementations in Singapore to the more flexible approaches in Nordic countries [27]. However, the specific configuration of intervention components that proved effective in our Ukrainian context may require adaptation for other settings. For instance, our intervention's emphasis on collaborative learning and peer support reflects cultural values around collective problem-solving that may be less prominent in more individualistic educational cultures.

The challenges faced during implementation, including infrastructure limitations and varying levels of prior digital exposure among students, mirror those reported in studies from other transitional economies [26]. This suggests that successful digital competence interventions in resource-constrained contexts require careful attention to basic infrastructure and support systems. However, our results demonstrate that significant improvements are possible even with modest resources when pedagogical approaches are well-designed and theoretically grounded. This finding offers hope for institutions in similar contexts that may feel constrained by limited technological resources.

The comparison with international frameworks and implementations highlights areas where our approach offers unique contributions. While many European implementations of DigComp focus heavily on assessment and certification, our emphasis on integrated pedagogical intervention provides a complementary perspective on how actually to develop the competencies that frameworks describe. Similarly, while some Asian approaches emphasise technical skill development through intensive training, integrating motivational and ethical dimensions offers a more holistic model that may better prepare students for the complex realities of professional digital work.

5.4. Addressing challenges and limitations

Despite the positive findings, several challenges emerged during the implementation that warrant discussion. While sufficient for detecting large effects, the relatively small sample size limits our ability to conduct more nuanced analyses of moderating factors or individual differences in response to the intervention. Future research with larger samples could explore how prior experience, learning styles, or career aspirations influence digital competence development. Additionally, while allowing for careful implementation control, the single-institution context raises questions about generalizability that can only be addressed through replication in diverse settings.

The 16-week duration of the intervention, while substantial for a single-semester study, may not capture the whole trajectory of digital competence development. Some competencies, particularly those related to ethical reasoning and security awareness, may require more extended development and practice to integrate fully into students' professional practice. Longitudinal follow-up studies could examine whether the gains observed in our study persist and translate into professional contexts. Such studies could also explore how digital competence develops as students encounter new technologies and challenges in their advanced coursework and careers.

The reliance on self-report measures for some aspects of assessment, particularly in the information-search and security-value dimensions, introduces potential biases that must be acknowledged. While we attempted to mitigate these biases through behavioural observations and triangulation with performance data, self-report measures remain vulnerable to social desirability effects and may not fully capture actual competence. Future research should continue to develop and validate more objective measures of digital competence that can complement self-report data while remaining practical for educational contexts.

5.5. Emerging technologies and future directions

The rapid emergence of generative AI technologies during our study period highlighted the opportunities and challenges of preparing students for a constantly evolving digital landscape. While our intervention did not explicitly include AI-related competencies, students in the experimental group showed greater adaptability when introduced to AI tools in subsequent courses. This suggests that the meta-cognitive and critical thinking skills developed through our intervention may provide a foundation for adapting to new technologies. Future iterations of digital competence frameworks and interventions must grapple with how to prepare students for technologies that do not yet exist [1].

The increasing importance of data literacy and algorithmic thinking in professional contexts suggests areas where computer science education must continue to evolve. While our framework included data handling elements within the information-search dimension, the growing centrality of data in all aspects of digital work may warrant more explicit attention. Similarly, understanding algorithmic decision-making and its societal implications represents an emerging competency that bridges technical and ethical dimensions. Future research should explore how these emerging competencies can be integrated into comprehensive digital competence frameworks.

The post-pandemic educational landscape has permanently altered expectations and possibilities for digital learning. Our study, conducted in a context still adapting to post-pandemic realities, suggests that blended and flexible approaches to digital competence development may be particularly effective. The combination of structured in-person collaboration with flexible online resources appeared to meet diverse student needs while building independent and collaborative competencies. Future research should systematically explore how different modalities and combinations can optimise digital competence development for diverse learners.

6. Conclusions and recommendations

6.1. Summary of key findings

This study provides compelling evidence for the effectiveness of an integrated pedagogical approach in developing digital competence in computer science students. The experimental intervention, which combined motivation enhancement strategies with innovative pedagogical technologies, produced significant improvements across all three dimensions of digital competence: cognitive-educational, information-search, and security-value. The large effect sizes observed (ranging from 0.72 to 0.85) indicate that these improvements were statistically significant and practically meaningful. Perhaps most importantly, the improvements were broadly distributed among participants rather than concentrated in a few high achievers, suggesting that the approach can benefit diverse learners.

This research's theoretical contributions extend beyond demonstrating intervention effectiveness. Our findings support a more integrated and dynamic understanding of digital competence that challenges compartmentalised approaches to skill development. The strong interconnections between different competence dimensions and distinct developmental trajectories suggest that digital competence emerges from the complex interplay of knowledge, skills, attitudes, and experiences rather than isolated skill acquisition. This understanding has important implications for conceptualising, teaching, and assessing digital competence in educational settings.

The practical significance of these findings for computer science education cannot be overstated. In an era where digital technologies evolve rapidly and unpredictably, developing students' foundational digital competence becomes even more critical than teaching specific technical skills. Our intervention approach, which emphasised conceptual understanding, critical thinking, and ethical reasoning alongside practical skills, appears to prepare students not just for current technologies but for adapting to future technological landscapes. The success of relatively resource-modest interventions also suggests that effective digital competence education is achievable across diverse institutional contexts.

6.2. Recommendations for practice

Our findings offer several concrete recommendations for educators and institutions seeking to enhance digital competence development in computer science education. First, institutions should adopt integrated pedagogical approaches that combine motivational support with innovative teaching methods rather than focusing solely on technical skill development. This requires professional development for faculty to build their capacity in implementing student-centred, problem-based pedagogies. Institutions might consider establishing communities of practice where faculty can share experiences and collaboratively develop effective approaches.

Second, curriculum designers should ensure that digital competence development is woven throughout the computer science curriculum rather than confined to standalone courses. While dedicated courses like the one in our study can provide focused intervention, digital competence development should be reinforced and extended across multiple courses and contexts. This might involve redesigning assignments in traditional computer science courses to explicitly address digital competence dimensions, particularly the often-neglected security-value aspects. Integration with capstone projects or internships could provide authentic contexts for applying and consolidating digital competencies.

Third, assessment practices must evolve to capture the multidimensional nature of digital competence. Our three-dimensional framework provides a starting point, but institutions should develop comprehensive assessment strategies that combine knowledge testing, performance assessment, and reflection on ethical and security considerations. Regular formative assessment can help identify students who need additional support while providing feedback that guides continued development. Institutions might consider developing digital portfolios where students can document and reflect on their digital competence development over time.

Fourth, institutions should invest in creating supportive infrastructure for digital competence development, including technological resources and human support systems. While sophisticated simulation platforms can enhance learning, basic provisions such as reliable internet access, collaborative workspaces, and technical support can significantly impact student success. Equally important is establishing peer mentoring systems and learning communities that provide ongoing support for digital skill development. These support systems are particularly crucial for students from backgrounds with limited prior digital exposure.

6.3. Recommendations for future research

While this study provides insights into digital competence development, several areas warrant further investigation.

The role of individual differences in digital competence development deserves systematic investigation. While our study found broadly distributed improvements, understanding how prior experience, cognitive styles, cultural backgrounds, and career aspirations influence learning trajectories could enable more personalised approaches to digital competence education. Research might explore whether different learner profiles benefit from different pedagogical approaches or whether certain universal principles apply across diverse learners.

The rapid evolution of artificial intelligence and other emerging technologies necessitates ongoing research into how digital competence frameworks and pedagogies must adapt. Studies should explore how to prepare students for human-AI collaboration, understanding of algorithmic decision-making, and navigation of increasingly complex digital ecosystems. Research might investigate whether new competence dimensions are needed or existing frameworks can accommodate these emerging requirements through expanded interpretations.

Comparative international research could provide valuable insights into how cultural, economic, and educational contexts influence effective approaches to digital competence development. While our study was situated in the Ukrainian context, systematic comparison with implementations in other countries could identify universal principles versus context-specific adaptations. Such research could inform the development of flexible frameworks that maintain core principles while allowing for local adaptation.

6.4. Final reflections

Developing digital competence in computer science students represents both a critical educational challenge and an opportunity to prepare graduates who can contribute meaningfully to our increasingly digital society. This study demonstrates that thoughtfully designed pedagogical interventions can significantly improve digital competence, even in resource-constrained contexts. However, developing digital competence cannot be confined to individual courses or interventions; it requires sustained institutional commitment and ongoing adaptation to technological change.

As we look toward the future of computer science education, integrating digital competence development with technical skill training becomes increasingly critical.

The students in our study will graduate into a world where technological capabilities alone are insufficient; they will need critical thinking, ethical reasoning, and adaptive capacity to navigate complex digital challenges. By investing in comprehensive approaches to digital competence development, we prepare graduates for their first jobs and lifelong learning and leadership in the digital age.

The journey toward effective digital competence education is ongoing, requiring continuous reflection, adaptation, and innovation. This study represents one contribution to that journey, offering evidence that transformative education is possible when we combine theoretical insight with practical innovation. As educators and researchers, our challenge is to continue pushing the boundaries of what is possible, ensuring that all students have the opportunity to develop the digital competencies they need to thrive in an interconnected, technology-mediated world.

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