
**TEAM INTERACTION AS A COMPONENT
OF MODERNIZING THE PROFESSIONAL TRAINING
OF THE PRE-SERVICE COMPUTER SCIENCE TEACHER**

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INTRODUCTION

The digital transformation of education in recent years has substantially changed how the content and organisation of teacher professional training are understood. This is not only about the wider use of platforms, services, cloud environments, electronic resources, or communication tools. The deeper changes concern the very logic of pedagogical activity, the ways in which professional interaction is organised, the structure of responsibility, the forms of collective problem-solving, and the teacher's role in a digitally rich educational environment. In this situation, the professional training of pre-service computer science teachers can no longer be limited to the development of instrumental skills related to the use of particular programs, services, or programming languages. It requires a more integrated approach that takes into account the ability to act in networked communication, to create digital products collectively, to design educational solutions jointly, to coordinate team actions, and to facilitate interaction in the digital space.

For the training of pre-service computer science teachers, this issue is especially pronounced. Computer science education has historically been linked to technology, algorithmisation, computational thinking, modelling, digital content, and work with information systems. However, the contemporary school, as well as the system of teacher education, places much broader demands on computer science teachers. They are expected not only to teach the subject, but also to organise the digital educational environment, participate in professional collaboration, coordinate interdisciplinary initiatives, facilitate team-based activity among learners, and often lead digital change within an educational institution. This means that the professional training of computer science teachers should include the development not only of subject-specific, methodological, and technological skills, but also of the capacity for team interaction as a stable professional quality.

1. Analysis of Current Research

The relevance of studying team interaction in the professional training of pre-service computer science teachers is strengthened by the fact that modern models of teacher education are moving further away from a narrow view of digital training as a set of technical skills. In recent studies, teachers' digital competence is understood as a multidimensional construct. It includes not only the use of digital tools, but also pedagogical design, communication, collaboration, digital content creation, professional development, the ethical use of technologies, safety, reflection, and the ability to solve complex educational tasks^{1,2}. This approach is particularly important for the training of pre-service computer science teachers, as it shifts the focus from the possession of digital tools to the ability to organise meaningful pedagogical interaction through them. In this sense, team interaction is not a secondary addition to digital literacy, but one of its professionally significant manifestations.

A separate group of studies focuses specifically on the training of computer science teachers. In their international review of models of computer science teacher education, Yadav et al.³ show that the systems used to train such specialists differ substantially across countries in their structure, duration, level of institutional support, and the relationship between subject-specific and pedagogical components. At the same time, the authors emphasise that effective computer science teacher education should include not only knowledge of computer science content, but also the ability to create educational situations focused on learners, equity, inclusion, the pedagogically appropriate use of technologies, and an understanding of the social consequences of digital solutions. This point is directly related to the problem of team interaction, since the modern computer science teacher should not only transmit knowledge about algorithms, data, programming, or digital systems, but also organise joint activity in which learners create, discuss, test, and improve digital products.

The need to rethink teacher professional training became especially clear after rapid educational shifts linked to the mass transition to distance, blended, and flexible learning. These processes showed that access to platforms or communication channels does not, by itself, ensure the quality of the educational

¹ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

² Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

³ Yadav A., Connolly C., Berges M., Chytas C., Franklin C., Hijón-Neira R., Macann V., Margulieux L. E., Ottenbreit-Leftwich A. T., Warner J. R. A review of international models of computer science teacher education. *ITCSE-WGR*, 2022. <https://doi.org/10.1145/3571785.3574123>

process. Difficulties often arise not so much because of a lack of technical resources, but because of insufficiently developed methodological, organisational and communication skills needed for work in a digitally mediated environment. Hodges et al.⁴ note that teacher education systems were often not ready to develop stable skills in digital teaching, flexible learning organisation and professional interaction in new modes of educational activity. Thus, digital transformation has revealed not only technical, but also conceptual gaps in teacher training.

In this regard, studies based on the model of technological, pedagogical, and content knowledge are particularly informative. Meletiou-Mavrotheris and Paparistodemou⁵, summarising 18 years of experience in TPACK-guided professional development for STEM/STEAM teachers, show a gradual move from short seminars on the use of particular software to systemic, school-based and collaborative programmes of professional learning. For this study, it is important that the authors directly connect the sustainability of professional development with teacher autonomy, collaboration, reflection, a socio-constructivist understanding of learning, and practical involvement in developing educational solutions. This finding strengthens the argument that pre-service computer science teacher training cannot be reduced to mastering tools. It should develop the ability to combine technology, pedagogical purpose, subject content, and the team organisation of activity.

A similar line of argument is developed by Norhagen, Krumsvik and Røkenes⁶, who, in their review of studies on professional digital competence in Norwegian teacher education, stress its dynamic and multidimensional nature. The authors note that teacher education should not only assess future teachers' self-perceptions of their digital skills, but also create conditions for their practical application in professionally meaningful situations. This is important for the present issue because team interaction is also not formed through a declarative introduction to its importance. It requires specially organised tasks, digital environments, ways of recording participants' contributions, and reflection on the process of joint work.

Recent research confirms that a teacher's readiness for effective activity in a digital environment depends on a combination of factors: digital literacy,

⁴ Hodges C. D., Barbour M., Pratt K. The persistent deficit: Historical gaps in the preparation of K-12 educators for digital teaching. *Journal of Online Learning Research*, 2026. <https://doi.org/10.70725/361467zxvzis>

⁵ Meletiou-Mavrotheris M., Paparistodemou E. Sustaining teacher professional learning in STEM: Lessons learned from an 18-year-long journey into TPACK-guided professional development. *Education Sciences*, 2024. Vol. 14, № 4. Article 402. <https://doi.org/10.3390/educsci14040402>

⁶ Norhagen S. L., Krumsvik R., Røkenes F. Developing professional digital competence in Norwegian teacher education: A scoping review. *Frontiers in Education*, 2024. Vol. 9. Article 1363529. <https://doi.org/10.3389/feeduc.2024.1363529>

methodological training, adaptability, innovativeness, communication skills, and the ability to work collaboratively. In this regard, Soroko and Shymon's⁷ findings are indicative. When analysing teachers' readiness to work in a STEAM-oriented environment, they stress the close connection between digital training, communication, innovativeness, and methodological capacity. Zhou et al.⁸, in a meta-analysis of experimental studies on the professional development of STEM teachers, also demonstrated the positive effect of professional learning on teachers' self-efficacy. This result is important because developed self-efficacy supports a teacher's readiness to take part in more complex forms of activity, including team-based design, digital collaboration, and the implementation of new pedagogical solutions.

At the same time, researchers note that digital competence does not always automatically lead to the pedagogically appropriate use of technology. Ghazali et al.⁹, analysing teachers' self-efficacy in using ICT for education for sustainability, showed that ICT knowledge and knowledge of sustainability issues are important predictors of self-efficacy, but that a gap may remain between possession of digital tools and their pedagogical use. For the training of pre-service computer science teachers, this has direct relevance: a learner may have sufficient instrumental skills, but still be unprepared to organise team work, support group dynamics, distribute roles, or facilitate the collective creation of an educational product.

Studies that connect teachers' digital competence with learners' involvement in active, responsible, and collaborative activity are especially important for the issue examined here. Lin et al.¹⁰ demonstrated that digital teaching competence acts as the main mediator between teachers' ICT skills, data literacy, and their ability to support the development of learners' digital capacity, ethical technology use, communication, and collaboration. This means that pre-service computer science teachers should be prepared not only to use digital tools, but also to create conditions in which technologies support interaction, responsibility, shared thinking, and collective problem-solving.

⁷ Soroko N., Shymon O. Teachers' readiness to use digital tools in a STEAM-oriented educational environment. *Educational Analytics of Ukraine*, 2025. № 1. P. 28–42. <https://doi.org/10.32987/2617-8532-2025-1-28-42>

⁸ Zhou X.-J., Shu L., Xu Z., Padrón Y. N. The effect of professional development on in-service STEM teachers' self-efficacy: A meta-analysis of experimental studies. *International Journal of STEM Education*, 2023. Vol. 10. Article 37. <https://doi.org/10.1186/s40594-023-00422-x>

⁹ Ghazali M., Makrakis V., Kostoulas-Makrakis N., Yakob N., Rashid R. A. A., Othman W., Fitriyanto N. Predicting teacher's information and communication technology-enabled education for sustainability self-efficacy. *Sustainability*, 2024. Vol. 16, № 13. Article 5323. <https://doi.org/10.3390/su16135323>

¹⁰ Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

Team interaction is a special focus in this system. The modern educational process is becoming less and less effective when organised according to the logic of isolated individual teacher work. The development of digital courses, the creation of integrated tasks, the introduction of project-based learning, the organisation of blended or distance formats, the use of analytical tools, the coordination of interdisciplinary initiatives, and the support of learners' joint activity all require interaction with others. Khasawneh et al.¹¹, studying teacher collaboration in professional learning communities and collaborative teaching practices, stress that effective collaboration requires time, supportive leadership, resources, and organisational recognition. For computer science teachers, this is especially important, as their professional field is closely linked with joint design, team development of digital products, the coordination of technological decisions, and participation in networked professional communities.

At the same time, in teacher education, team interaction has long remained mainly an implicit requirement. It has often been assumed as a desired outcome of group forms of work, but has less often been considered as a separate object of purposeful development, with its own structure, criteria, indicators, and methodological means. As a result, educational practice often equates team interaction with any form of group activity. This approach is insufficient. Team interaction involves not only the joint presence of several participants and not only the distribution of separate functions, but also a shared goal, coordinated actions, role distribution, mutual responsibility, the ability to coordinate, and readiness to produce a collective result. For this reason, its development requires a specially organised pedagogical process.

This idea is supported by studies of collaborative learning in computer science, programming, and computational thinking. Andersen, Mørch, and Litherland¹², studying collaborative learning with block-based programming, showed that in an online environment, technological artifacts and group discussions develop in parallel and influence each other. This is important for the present study because the team interaction of pre-service computer science teachers is formed not only through communication but also through the joint creation of a digital product, work with visual objects, decision coordination, and the gradual refinement of the logic of a digital artifact. Thus, in computer

¹¹ Khasawneh Y. J. A., Alsarayreh R., Al Ajlouni A. A., Eyadat H., Ayasrah M., Khasawneh M. An examination of teacher collaboration in professional learning communities and collaborative teaching practices. *Journal of Education and e-Learning Research*, 2023. Vol. 10, № 3. P. 446–452. <https://doi.org/10.20448/jeelr.v10i3.4841>

¹² Andersen R., Mørch A., Litherland K. Collaborative learning with block-based programming: Investigating human-centered artificial intelligence in education. *Behaviour & Information Technology*, 2022. <https://doi.org/10.1080/0144929X.2022.2083981>

science teacher education, teamwork is not abstract, but mediated by subject-specific activity.

In a digital educational environment, this issue becomes more complex. On the one hand, digital technologies substantially expand opportunities for joint activity. They allow participants to work synchronously and asynchronously, edit documents collectively, visualise ideas, record intermediate results, track revision history, see participants' contributions, and support distributed interaction. On the other hand, the digital environment itself creates new requirements for communication culture, clarity of wording, coordination of actions, the ability to avoid communication gaps, and the ability to maintain team dynamics without constant face-to-face presence. Therefore, the digital environment does not simplify team interaction. It changes its form, makes some aspects of collaboration visible, and at the same time sharpens others.

Current research increasingly stresses that digital tools are pedagogically effective when they are included in the logic of meaningful joint activity. Abildinova et al.¹³ emphasise the importance of active methods and teachers' practical entry into a digitally rich environment. Amemasor et al.¹⁴, in a systematic review, show that teacher professional development in digital integration is most effective when it combines practice, collaborative formats, methodological support, mentoring, and institutional support. Theodorio¹⁵ also stresses that successful technology integration into pedagogical activity requires not episodic assistance, but continuous and proactive support. These findings are particularly important for the training of pre-service computer science teachers, as they point to the need to move the focus from one-off instruction or technical training to the systematic organisation of experience in joint digital activity.

A significant research area concerns the development of project-based, problem-based, inquiry-based, and case-based learning. Zhang et al.¹⁶, analysing online-offline case discussions in postgraduate computer science courses, showed that learners construct knowledge more actively when they can work with real engineering cases, discuss different approaches, choose a learning pathway, and

¹³ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

¹⁴ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

¹⁵ Theodorio A. O. Examining the support required by educators for successful technology integration in teacher professional development program. *Cogent Education*, 2024. Vol. 11, № 1. Article 2298607. <https://doi.org/10.1080/2331186X.2023.2298607>

¹⁶ Zhang X., Zhang B., Zhang F. Student-centered case-based teaching and online-offline case discussion in postgraduate courses of computer science. *International Journal of Educational Technology in Higher Education*, 2023. Vol. 20. Article 6. <https://doi.org/10.1186/s41239-022-00374-2>

develop higher-order thinking. Halawa, Lin, and Hsu¹⁷, in a systematic review of instructional design in STEM education, demonstrated the widespread use of design-based, inquiry-based, project-based, and problem-based learning to achieve STEM literacy and develop twenty-first-century competencies. Lavado-Anguera, Velasco-Quintana, and Terrón-López¹⁸ also show that project-based learning in engineering education supports the development of real professional skills, especially when it is connected with technologies, interdisciplinarity, simulation, and professional environments. These studies confirm the value of using team-based project tasks in the training of pre-service computer science teachers.

It is also necessary to consider studies linking project-based learning to the development of computational thinking. Ye et al.¹⁹, analysing the integration of computational thinking into K-12 mathematics education, showed that productive learning takes place when learners not only follow instructions, but also create computational artifacts, interpret their results, and combine mathematical and computational reasoning. Fitrah et al.²⁰ demonstrated that the combination of project-based learning and flipped classroom has a positive effect on the development of decomposition, pattern recognition, and abstraction. For the training of computer science teachers, this means that team interaction should be developed through tasks in which learners jointly analyse a problem, construct a solution, visualise intermediate results, and create a digital product.

This is also connected with the broader discourse of student-centred learning. Bhardwaj et al.²¹ view the student-centred approach as one that supports active participation, peer collaboration, independence, critical thinking, and learners' professional growth. Treve²², comparing teacher-centred

¹⁷ Halawa S., Lin T.-C., Hsu Y.-S. Exploring instructional design in K-12 STEM education: A systematic literature review. *International Journal of STEM Education*, 2024. Vol. 11. Art. 43. <https://doi.org/10.1186/s40594-024-00503-5>

¹⁸ Lavado-Anguera S., Velasco-Quintana P.-J., Terrón-López M. Project-based learning (PBL) as an experiential pedagogical methodology in engineering education: A review of the literature. *Education Sciences*. 2024. Vol. 14, № 6. Article 617. <https://doi.org/10.3390/educsci14060617>

¹⁹ Ye H., Liang B., Ng O.-L., Chai C. S. Integration of computational thinking in K-12 mathematics education: A systematic review on CT-based mathematics instruction and student learning. *International Journal of STEM Education*, 2023. Vol. 10. Article 3. <https://doi.org/10.1186/s40594-023-00396-w>

²⁰ Fitrah M., Sofroniou A., Setiawan C., Widiastuti, Yarmanetti, N., Sari Jaya M. P., Panuntun J. G., Arfaton A., Beteno S., Susianti I. The impact of integrated project-based learning and flipped classroom on students' computational thinking skills: Embedded mixed methods. *Education Sciences*, 2025. Vol. 15, № 4. Article 448. <https://doi.org/10.3390/educsci15040448>

²¹ Bhardwaj V., Zhang S., Tan Y., Pandey V. Redefining learning: Student-centered strategies for academic and personal growth. *Frontiers in Education*, 2025. Vol. 10. Article 1518602. <https://doi.org/10.3389/educ.2025.1518602>

²² Treve M. Comparative analysis of teacher-centered and student-centered learning in the context of higher education: A co-word analysis. *Iberoamerican Journal of Science Measurement and Communication*, 2024. Vol. 4, № 1. Article 117. <https://doi.org/10.47909/ijsmc.117>

and student-centred learning, shows that the former is more closely linked with teachers' pedagogical actions and standardised assessment, while the latter focuses on learners' progress, formative feedback, access to support, and the educational environment. This is important for the present topic, since team interaction among pre-service computer science teachers cannot be formed in a model in which the learner is only a performer of instructions. It requires space for decision-making, shared responsibility, mutual learning, and reflection.

Peer learning and mentoring are also directly connected with team interaction. Tanveer et al.²³, analysing peer teaching in medical education, showed that learners who take on the role of teaching others develop not only subject knowledge, but also pedagogical, personal, and general skills. Krishna et al.²⁴, in a study of peer mentoring, stress the importance of communities of practice, structured mentoring, and mutual support for professional identity. Although these studies do not directly concern computer science teacher education, they are methodologically useful because they show that when a learner takes on the role of a mentor, coordinator, or participant in mutual support, they engage more deeply in professional activity. In the training of pre-service computer science teachers, this can be implemented through peer teaching, work in small teams, mutual consultation on digital tools, and joint reflection on the results.

The Ukrainian research discourse also provides strong grounds for considering this issue within the broader framework of modernising teacher education. Studies on the development of teachers' information and digital culture, the organisation of the digital educational environment, and the use of computer visualisation tools show that the quality of digitalisation is determined not only by the set of tools used, but primarily by the pedagogical logic of their implementation^{25,26}. For the pre-service computer science teacher, this means that the digital environment should be understood not as a set of technical

²³ Tanveer M., Mildestvedt T., Skjærseth I. G., Arntzen H. H., Kenne E., Bonnevier A., Stenfors T., Kvernenes M. Peer teaching in undergraduate medical education: What are the learning outputs for the student-teachers? A systematic review. *Advances in Medical Education and Practice*, 2023. Vol. 14. P. 723–739. <https://doi.org/10.2147/AMEPS401766>

²⁴ Krishna L., Pisupati A., Teo K. J. H., Teo M. Y. K., Quek C., Chua K. Z. Y., Venkaramana V., Raveendran V., Singh H., Wong S. L. C., Ng V. W. W., Ting O., Loh E. K. Y., Yeoh T. T., Owyong J. L. J., Ong E., Phua G., Hill R., Mason S., Ong S. Y. K. Professional identity formation amongst peer-mentors in a research-based mentoring programme. *BMC Medical Education*, 2023. Vol. 23. Article 764. <https://doi.org/10.1186/s12909-023-04718-y>

²⁵ Богославський С., Семеніхіна О., Юрченко А. Порівняльний аналіз українських та європейських практик організації цифрового освітнього середовища. *Науковий вісник Південноукраїнського національного педагогічного університету імені К. Д. Ушинського*, 2025. Випуск 2 (151). С. 38–42. <https://doi.org/10.24195/2617-6688-2025-2-6>

²⁶ Юрченко А., Момот Р., Семеніхіна О. Про розвиток інформаційно-цифрової культури вчителів з використанням комп'ютерної візуалізації. *Освіта. Інноватика. Практика*, 2024. Том 12, № 6. С. 93–99. <https://doi.org/10.31110/2616-650X-vol12i6-014>

resources, but as a space of professional action, where content, interaction, coordination, visualisation and responsibility for a shared result are connected.

The link between team interaction and the development of soft skills is also important, since modern pedagogical activity can no longer be considered complete without them. Communication, collaboration, the ability to work in a group, responsibility for a shared result, emotional sensitivity to other participants, readiness to accept revisions, and the ability to agree on decisions do not exist separately from professional training. On the contrary, in a digitally rich educational environment, they become a condition for the effective use of technologies themselves. The study by Yurchenko et al.²⁷ shows that specially organised team activity can have a positive effect on the development of soft skills, while the work of Semenog et al.²⁸ emphasises the developmental potential of communicative tasks for the formation of more complex personal and professional qualities. Similar ideas are found in Rusmin et al.²⁹, where critical thinking and problem-solving are considered skills that require purposeful inclusion in the educational process, proper resources, teacher preparation, and appropriate assessment methods.

The problem of team interaction is also important because it is directly linked to the transformation of the teacher's professional role. In the traditional model, the teacher is often seen as the main holder of content, the controller of task completion, and the organiser of individual learning activity. In the digital educational environment, this role becomes much more complex. The teacher has to coordinate different channels of interaction, create and adapt digital materials, work in a mode of joint editing, support asynchronous communication, analyse digital traces of activity, facilitate group processes, and often act within a system of distributed responsibility. Shal et al.³⁰, studying teacher leadership in virtual communities of practice, showed that online communities can support teacher agency, distributed leadership, project initiation, knowledge exchange, and the organisation of professional development. This is important for the pre-service computer science teacher, who in school often becomes not only

²⁷ Юрченко А., Момот Р., Острога М., Семеніхіна О. Візуалізація знань засобами вебтехнологій у формуванні критичного мислення майбутніх учителів інформатики. *Фізико-математична оцінка*, 2025. Том 40, №5. С. 80-88. <https://doi.org/10.31110/fmo2025.v40i5-11>

²⁸ Semenog O., Hrona N., Khomych T., Stasiuk T., Yurchenko A., Semenikhina O. Communicative tasks as a means of developing the emotional intelligence of students. *International Journal of Modern Education and Computer Science*, 2024. Vol. 16, No. 4. P. 46–57. <https://doi.org/10.5815/ijmecs.2024.04.04>

²⁹ Rusmin L., Misrahayu Y., Pongpalilu F., Radiansyah R., Dwiyanto D. Critical thinking and problem-solving skills in the 21st century. *Journal of Social Science*, 2024. Vol. 5, № 3. <https://doi.org/10.59613/svhy3576>

³⁰ Shal T., Ghamrawi N., Abu-Tineh A. M., Al-Shaboul Y. M., Sellami A. Teacher leadership and virtual communities: Unpacking teacher agency and distributed leadership. *Education and Information Technologies*, 2024. Vol. 29. P. 6037–6064. <https://doi.org/10.1007/s10639-023-12446-5>

a performer of subject-specific tasks, but also a participant in, or initiator of, digital change.

Studies of emerging areas of computer science education, especially artificial intelligence, also support this logic. Jetzinger, Baumer, and Michaeli³¹ describe a scalable professional development programme for computer science teachers preparing to teach AI in compulsory K-12 education. They emphasise the combination of subject knowledge, pedagogical knowledge, blended learning, and support for teachers with different levels of prior training. Yim and Su³², in a scoping review of AI learning tools in K-12 education, show that AI literacy is most often supported through project-based, constructivist, human-computer collaborative, game-based, and practice-oriented approaches. For the training of pre-service computer science teachers, this means that new topics, including artificial intelligence, cannot be effectively integrated into the educational process without teamwork, discussion, joint model creation, reflection on ethical aspects, and pedagogical facilitation.

More recent studies also show an interest in the interaction between humans, artificial intelligence, and learning analytics. Cohn et al.³³ propose a multimodal approach to supporting collaboration between the teacher, the researcher and AI in STEM+C environments. They show that artificial intelligence can be useful for identifying difficulties in learners' joint work, but that these difficulties require teacher interpretation. Paolucci et al.³⁴, analysing the opportunities and risks of learning analytics in K-12 education, emphasise the potential of analytics for individualised learning, formative assessment, and support for equity. At the same time, they warn against misinterpreting data, violating privacy, and excessive reliance on digital indicators. This is important for the present study because team interaction in a digital environment leaves digital traces that require careful pedagogical interpretation. They do not replace the teacher's professional judgment, but extend the opportunities for observation and reflection.

In pre-service computer science teacher training, it is also important to consider that the digital educational environment can support not only

³¹ Jetzinger F., Baumer S., Michaeli T. Artificial intelligence in compulsory K-12 computer science classrooms: A scalable professional development offer for computer science teachers. *Proceedings of the 55th ACM Technical Symposium on Computer Science Education*, 2024. Vol. 1. P. 1461–1467. <https://doi.org/10.1145/3626252.3630782>

³² Yim I. H. Y., Su J. Artificial intelligence (AI) learning tools in K-12 education: A scoping review. *Journal of Computers in Education*, 2024. Vol. 12, p. 93–131. <https://doi.org/10.1007/s40692-023-00304-9>

³³ Cohn C., Snyder C., Fonteles J., Montenegro J., Biswas G. A multimodal approach to support teacher, researcher and AI collaboration in STEM+C learning environments. *British Journal of Educational Technology*, 2024. Vol.56, Is. 2. Pp. 595-620. <https://doi.org/10.1111/bjet.13518>

³⁴ Paolucci C., Vancini S., Bex R. T., Cavanaugh C., Salama C. D., de Araujo Z. A review of learning analytics opportunities and challenges for K-12 education. *Heliyon*, 2024. Vol. 10, № 4. Article e25767. <https://doi.org/10.1016/j.heliyon.2024.e25767>

collaboration but also self-regulation, metacognition, and a reflective culture. Zarestky et al.³⁵, in a study of reflective writing in computational science and engineering courses, found that reflective practices support the development of metacognitive awareness, self-regulated learning, critical thinking, and problem-solving. Arefian, Çomoğlu, and Dikilitaş³⁶, analysing ChatGPT-driven collaborative reflective practice in a community of practice, also showed that individual reflection with ChatGPT can prepare participants for more meaningful collective reflection. These results are important for developing a methodology for team interaction, since team activity requires not only the joint completion of a task but also reflection on one's own contribution, roles, difficulties, communication decisions, and the quality of the shared product.

A separate layer of research concerns institutional conditions, without which team and digital interaction cannot become sustainable. Diab and Green³⁷, analysing support for novice teachers, show the importance of formal and informal support networks, mentoring, induction programmes, emotional safety, and professional guidance. Dahri et al.³⁸ demonstrate that motivation to adopt blended learning in teacher professional development depends on a combination of internal and external factors, as well as on the characteristics of the educational environment. Revina et al.³⁹, studying long-term problems in teacher professional development reforms in Indonesia, show that the formal existence of programmes does not guarantee quality if coherence, relevance, consideration of teachers' prior experience, feedback, and follow-up support are absent. All these findings confirm that the development of team interaction in pre-service computer science teachers requires not isolated exercises, but an integrated pedagogical organisation.

Thus, the analysis of current research shows that the problem of team interaction in pre-service computer science teachers lies at the intersection

³⁵ Zarestky J., Bigler M., Brazile M., Lopes T., Bangerth W. Reflective writing supports metacognition and self-regulation in graduate computational science and engineering. *Computers and Education Open*, 2022. Vol. 3. Article 100085. <https://doi.org/10.1016/j.caeo.2022.100085>

³⁶ Arefian M. H., Çomoğlu I., Dikilitaş K. Understanding EFL teachers' experiences of ChatGPT-driven collaborative reflective practice through a community of practice lens. *Innovation in Language Learning and Teaching*, 2024. Vol. 20(2). Pp. 318–333. <https://doi.org/10.1080/17501229.2024.2412769>

³⁷ Diab A.-K., Green E. Cultivating resilience and success: Support systems for novice teachers in diverse contexts. *Education Sciences*, 2024. Vol. 14, № 7. Article 711. <https://doi.org/10.3390/educsci14070711>

³⁸ Dahri N. A., Yahaya N., Al-Rahmi W. M., Noman H., Alblehai F., Kamin Y., Soomro R. B., Shutaleva A., Al-Adwan A. S. Investigating the motivating factors that influence the adoption of blended learning for teachers' professional development. *Heliyon*, 2024. Vol. 10, № 15. Article e34900. <https://doi.org/10.1016/j.heliyon.2024.e34900>

³⁹ Revina S., Pramana R., Bjork C., Suryadarma D. Replacing the old with the new: Long-term issues of teacher professional development reforms in Indonesia. *Asian Education and Development Studies*, 2023. Vol. 12, № 4/5. P. 257–274. <https://doi.org/10.1108/AEDS-12-2022-0148>

of several research areas: digital pedagogical competence, computer science teacher education, TPACK-guided professional development, collaborative learning, project activity, professional communities, soft skills, learning analytics, and new technological fields, including artificial intelligence. At the same time, despite growing interest in teachers' digital competence, collaboration in the educational environment, distributed leadership, and the use of collaborative digital tools, the problem of team interaction as a component of the professional training of pre-service computer science teachers has not yet received sufficiently integrated attention. Its content, structure, assessment criteria, pedagogical conditions, and development methodology still require clarification.

Therefore, the research problem in this section is that a gap persists between the current requirements for the professional activity of computer science teachers and the actual practice of their training. Educational reality already requires a teacher capable of digitally mediated team interaction, yet the training system does not always give this capacity sufficient attention as an independent learning outcome. For this reason, the study of team interaction as a component of modernising the professional training of pre-service computer science teachers is timely and scientifically justified.

The aim of this section is to provide a theoretical justification for team interaction as a component of modernising the professional training of pre-service computer science teachers, to clarify its content and structure, to define the criteria and indicators of its formation, to characterise the pedagogical conditions and methodology for its development in a digital educational environment, and to analyse the results of the pilot testing of the proposed approach. Achieving this aim requires a consistent examination of several interrelated tasks: identifying the role of digital transformation in changing the professional model of the computer science teacher; clarifying the place of team interaction in the structure of the teacher's professional training; analysing the pedagogical potential of the digital educational environment; justifying the components, criteria and indicators of team interaction formation; describing the methodology for its development and interpreting the results of the pilot experiment.

The aim of this section is to provide a theoretical justification for team interaction as a component of modernising the professional training of pre-service computer science teachers, to clarify its content and structure, to define the criteria and indicators of its formation, to describe the pedagogical conditions and methodology for its development in a digital educational environment, and to analyse the results of the pilot testing of the proposed approach. Achieving this aim involves a consistent examination of several

interrelated tasks: identifying the role of digital transformation in changing the professional model of the computer science teacher; clarifying the place of team interaction in the structure of the teacher's professional training; analysing the pedagogical potential of the digital educational environment; justifying the components, criteria and indicators of team interaction formation; describing the methodology for its development; and interpreting the results of the pilot experiment.

2. Methods

The study is theoretical and applied. It aims to justify team interaction as a component of modernising the professional training of pre-service computer science teachers. Its methodological basis comprises competence-based, activity-based, environmental, and project-based approaches. These approaches made it possible to consider team interaction not as a separate social skill, but as an integrated professional capacity formed through digitally mediated joint activity.

To achieve the study's aim, a set of interrelated methods was used. A theoretical analysis of the research literature was applied to clarify the meanings of the concepts "team interaction", "digital educational environment", "digital pedagogical competence", "collaborative activity", and "professional training of pre-service computer science teachers". This method enabled the identification of current approaches to understanding teachers' digital competence, the determination of the role of collaboration and communication in its structure, and the justification of the need for purposeful development of team interaction among pre-service computer science teachers.

The methods of generalisation, systematisation and comparison were used to compare concepts that are close in meaning: group work, cooperation, collaboration, and team interaction. This made it possible to define the specific features of team interaction as a professionally significant characteristic of the future teacher. It includes a shared goal, role coordination, distributed responsibility, coordination of actions, joint creation of a digital product, and reflection on the team process.

The modelling method was used to develop the structure of team interaction in pre-service computer science teachers. On this basis, its interrelated components, criteria, and indicators of formation were identified. The model accounted for the specific features of the professional activity of computer science teachers, including the need for digital communication, the design of educational solutions, the joint creation of digital resources, the coordination of learners' group activity, and the use of tools within a digital educational environment.

The design method was used to describe the methodology for developing team interaction. It made it possible to define the pedagogical conditions, content lines, stages of work, types of tasks, and digital tools suitable for developing team interaction in pre-service computer science teachers. Particular attention was paid to tasks in which teamwork is not a formal requirement, but a necessary condition for achieving the result. These included the joint development of digital educational materials, the creation of visual models, work with digital boards, preparation of lesson fragments, collective editing of documents, and reflective analysis of the team process.

The empirical component of the study consisted of pilot testing the proposed approach. Its purpose was to check the pedagogical appropriateness of the developed methodology and to identify changes in particular manifestations of team interaction among pre-service computer science teachers. During the pilot testing, pedagogical observation, analysis of team activity products, analysis of digital artifacts of joint work, learners' reflective responses, and expert assessment of completed tasks were used. The digital artifacts included shared documents, comments, revision history, materials from digital boards, role distribution tables, and intermediate and final results of teamwork.

The assessment of team interaction formation was conducted according to a set of defined criteria and indicators. In particular, attention was paid to participants' ability to agree on a shared goal, distribute roles, maintain constructive digital communication, follow the logic of joint design, create a coherent digital product, respond to the suggestions of other participants, make reasoned revisions, and reflect on their own contribution to the team result. This approach made it possible to analyse not only the final product, but also the process of team interaction itself.

The results of the pilot testing were processed through qualitative analysis of observations, digital traces of activity, reflective materials, and expert conclusions. The main focus was not on statistical proof of the methodology's effectiveness, but on identifying the pedagogical logic of its use, describing changes in the nature of teamwork, and determining the conditions under which a digital educational environment genuinely supports the development of team interaction among pre-service computer science teachers.

Taken together, the methods used made it possible to move from a general theoretical understanding of the problem to the construction of a structured model of team interaction, the definition of criteria for its formation, the description of a development methodology, and the interpretation of the results of its pilot implementation in the professional training of pre-service computer science teachers.

3. Results

3.1. Team Interaction in the Structure of Modern Professional Training of Pre-service Computer Science Teachers

3.1.1. Digital Transformation of Education and the Changing Professional Model of the Pre-service computer science teacher

The digital transformation of education is one of the processes that changes not only the instrumental support of the educational process, but also the very structure of pedagogical activity. It should not be reduced to the mechanical introduction of separate platforms, services, electronic resources, or online communication methods. In a deeper sense, it involves a restructuring of the ways in which knowledge is created, transmitted, and understood; a transformation of models of professional interaction; changes in the nature of feedback; more complex coordination among participants in the educational process; and the gradual movement of pedagogical work into networked, flexible, and technologically mediated modes of functioning. For this reason, digital transformation should be viewed not as an external technological background, but as a factor that changes the professional model of the pre-service computer science teacher.

In contemporary research discourse, the idea is increasingly supported that a teacher's effective activity in a digital environment is not determined solely by technical skills. What is more important is the ability to integrate digital tools into the learning logic in ways that support the achievement of educational goals, promote meaningful interaction, and open up opportunities for independent work, collaboration, critical thinking, and creativity. It is in this sense that teachers' digital competence ceases to be a purely technological characteristic and acquires pedagogical, communicative, organisational and reflective dimensions. This approach can be seen, in particular, in the work of Tzafilkou et al.⁴⁰, where digital competence is treated as a multidimensional construct, and in the study by Alom and Ramalingappa⁴¹, which stresses the complex structure of teachers' digital literacy and the need for its systematic understanding.

For pre-service computer science teachers, this change is especially significant, since their professional training is traditionally associated with a higher level of digital involvement. However, this initial connection

⁴⁰ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

⁴¹ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

with technology may create the false impression that computer science education automatically ensures readiness for work in the context of digital transformation. In fact, possession of digital tools and readiness for digitally mediated pedagogical activity are not the same. A pre-service computer science teacher may work successfully with programming environments, visualisation services, cloud resources, or learning management platforms, but at the same time may show insufficiently developed skills related to team coordination, facilitation of digital interaction, joint creation of an educational product, or pedagogically appropriate role distribution within a team. For this reason, digital transformation places not only higher, but also qualitatively new demands on this group of future teachers.

In a more traditional model of professional training, the computer science teacher was often viewed primarily as a specialist who should have a solid knowledge of the subject, possess algorithmic thinking, and be able to work with computer hardware, software, networks, digital resources, and methods of teaching relevant topics. These components undoubtedly remain the basis of professional training. However, they no longer cover the full content of the modern professional role. Today, the computer science teacher increasingly acts not only as a bearer of specialised knowledge, but also as an organiser of the digital educational environment, a participant in the development of shared educational solutions, a coordinator of group forms of activity, a consultant on the use of digital tools, and a promoter of digital culture and communication within the educational institution. This means that the teacher's professional model is shifting from individualised subject teaching towards a more complex form of pedagogical participation, in which technological, communicative, organisational and project dimensions interact with each other.

One of the most significant consequences of digital transformation is the changing nature of pedagogical communication. Previously, a large part of professional interaction was conducted face-to-face, through meetings, methodological groups, consultations, and direct oral discussion. Now, more and more communication processes are moving into the digital space. This concerns communication between the teacher and learners, professional interaction among colleagues, and the teacher's participation in the creation of shared courses, materials, learning events, projects or internal documentation. Digital communication has a different pace, a different structure, a different level of message recording and a different culture of coordination. In this form of communication, particular importance is given to clarity of wording, the ability to provide brief and precise feedback, the ability to maintain the team's working rhythm, to prevent misunderstandings, and to preserve a functional ethics of communication. Thus, the professional model of the pre-service computer

science teacher can no longer be based only on the idea of the teacher as an individual user of digital tools. It must include a culture of digital professional communication as an integral part of pedagogical activity.

The nature of professional responsibility also changes substantially. In a digital educational environment, the teacher works less often as a fully autonomous performer who independently defines almost all parameters of their own pedagogical activity. Instead, the teacher's work is increasingly included in a system of coordinated actions, shared platforms, regulations, environments, digital courses, resource databases, monitoring procedures, and collective coordination. This does not abolish pedagogical autonomy, but gives it a different character. It becomes less isolated and more connected to the activities of other participants. The pre-service computer science teacher must be ready not only to make decisions about the content or form of a particular lesson, but also to work within a system of digitally mediated shared responsibility, where their own actions are constantly related to the general logic of the team, platform, course, or joint project.

Digital transformation also affects the very understanding of the educational product. In the traditional format, the result of a teacher's professional activity was often associated with a lesson delivered, a lesson plan prepared, an assignment checked, or an individually created learning material. In the modern digital environment, the educational product increasingly has a collective nature. It may be a jointly developed digital course, a database of learning materials, an integrated project, a series of visualisations, interactive exercises, electronic instructions, analytical materials, digital cases or lesson scenarios. For the pre-service computer science teacher, this change is especially indicative, as a large part of their activity is connected with a structured, technologically shaped, and potentially collectively created result. This requires preparation for work in the mode of shared digital authorship and, therefore, for team interaction as a specific way of professional activity.

It is also important that digital transformation changes the relationship between technical skill and pedagogical appropriateness. Previously, digital tools were often seen as an additional resource that could be used, if desired, to diversify teaching. Now they are becoming the environment in which a substantial part of educational activity takes place. This means that the teacher no longer simply applies a tool, but acts within an instrumentally organised space. For this reason, as Lin et al.⁴² showed, what matters most is not only general ICT competence, but digital pedagogical competence, which mediates

⁴² Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

the teacher's ability to create conditions for collaboration, communication, and responsible use of technologies. For the pre-service computer science teacher, this is of fundamental importance: they must not only be technologically prepared themselves, but also be able to turn a digital tool into a means of organising meaningful joint activity.

The influence of digital transformation on the relationship between teachers' professional training and expectations of learners also deserves special attention. The modern school is oriented not only to the development of subject knowledge but also to digital literacy, communication, collaboration, critical thinking, the ability to work in a team, solve problems, and create products in a digital environment. Accordingly, the computer science teacher must not only be able to emphasize the importance of these skills but also to demonstrate them in their own professional activity. A teacher who does not have experience of team-based digital interaction is unlikely to be able to organise it effectively for learners. Thus, the future professional model of the computer science teacher is also determined by the need to be a bearer of the practices they are expected to develop in others.

In current conditions, the growing role of collaborative and networked forms of professional development is especially visible. Teachers increasingly learn not only through individual study of materials but also through professional communities, resource exchange, collective solutions to methodological problems, joint content creation, and mutual consultation in the digital environment. Amemasor et al.⁴³ draw attention to this point, stressing that effective professional development for teachers in the digital field is linked to collaborative formats, practical involvement, and systemic support. These findings are important not only for practising teachers, but also for the system of training future teachers. If the professional life of a teacher is becoming more networked and team-based, then professional training should equip teachers with the corresponding ways of acting before entering real educational practice.

For the pre-service computer science teacher, this tendency has an additional dimension. Unlike many other subject areas, computer science naturally tends towards joint construction, modelling, programming, work with visualisations, the building of digital systems, and the design of algorithmic solutions. Many types of activity in computer science education are inherently collective or, at least, benefit greatly from a team-based format. This concerns the creation of digital learning materials, the development of interdisciplinary projects, work with models, the organisation of STEM activities, the design of learning

⁴³ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/feduc.2025.1541031>

cases, and the use of analytical dashboards and digital boards. Accordingly, the professional model of such a teacher should include not only subject expertise but also readiness to work within a system for the joint creation and coordination of pedagogical decisions.

At the same time, digital transformation reveals several risks that make preparation for team interactions even more relevant. Fragmented tools, overloaded communication channels, inconsistent platforms, unclear communication rules, the absence of shared standards for preparing materials, or the absence of responsibility for coordination may not strengthen professional collaboration but, on the contrary, make it more difficult. For this reason, the digital environment can be both a factor supporting team work and a source of additional difficulties if it is organised chaotically. Research findings stress that what matters is not the individual mastering of separate services, but systemic institutional support for digital transformation, platform coherence, and a clear logic of professional interaction⁴⁴. For the system of training pre-service computer science teachers, this means that it is necessary to teach not simply a tool, but work in a functionally organised digital environment.

All of the above allow us to state that the digital transformation of education changes the professional model of the pre-service computer science teacher in at least several interconnected directions. First, it broadens the content of the professional role by adding to subject-specific and methodological training new functions related to the digital organisation of the educational process, communication, analytics, joint product creation, and coordination of interaction. Second, it changes the nature of professional autonomy, moving it into a mode of connected, networked, and distributed responsibility. Third, it strengthens the importance of team interaction as a professional quality, without which modern pedagogical activity in a digital environment loses its effectiveness. Fourth, it requires a reconsideration of the very logic of professional training, which should develop not only individual digital skills but also readiness for joint activity in a digitally organised educational space.

Thus, the digital transformation of education is not a secondary circumstance, but a systemic factor in changing the professional model of the pre-service computer science teacher. It changes functions, responsibility, communication, the nature of professional participation, and the expected outcomes of pedagogical activity. For this reason, in the structure of modernising the professional training of pre-service computer science teachers, particular

⁴⁴ Hodges C. D., Barbour M., Pratt K. The persistent deficit: Historical gaps in the preparation of K-12 educators for digital teaching. *Journal of Online Learning Research*, 2026. Vol. 12, No 1. Pp. 169-193. <https://doi.org/10.70725/361467zxvzis>

importance is given to the development of qualities that ensure effective activity in the digital environment not only individually, but also in interaction with others. One of these qualities is team interaction, which is therefore moving from the periphery of professional training to the number of its substantively significant components.

3.1.2. Team Interaction as a Professionally Significant Characteristic of the Pre-service computer science teacher

In modern teacher education, it is increasingly clear that the professional training of future teachers cannot be built solely on the mastery of subject content, teaching methods, and digital tools. Educational practice increasingly requires the ability to engage in joint design, coordinate activities, participate in the collective creation of educational solutions, support communication in the digital environment, and participate in professional communities. In this sense, team interaction should be considered not as an optional or auxiliary quality, but as a professionally significant characteristic of the pre-service computer science teacher. It is this characteristic that supports the move from an individualised model of professional training to one that corresponds to the real logic of modern pedagogical work under conditions of digital transformation in education^{45,46}.

For pre-service computer science teachers, this characteristic is particularly important for several reasons. First, computer science as an educational field is directly connected with activity that naturally tends towards cooperation, construction, the coordination of algorithms of action, the joint creation of digital products, the design of environments and collective problem-solving. Second, the pre-service computer science teacher will work in a professional field where digital tools often become the basis not only for individual work, but also for team interaction. Third, in many cases this teacher is expected to organise learners' group activity, advise on digital collaboration, and facilitate team-based solutions to learning tasks. Thus, for the pre-service computer science teacher, team interaction is not only a way of taking part in professional activity but also part of their future pedagogical influence.

In research discourse, the concept of team interaction needs to be clearly distinguished from other closely related categories. This is important

⁴⁵ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁴⁶ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

because educational practice often equates group work with teamwork. Such an approach simplifies the problem and prevents us from identifying which professional qualities pre-service computer science teachers should develop. Group interaction is the broadest concept and may refer to any form of joint presence or exchange of actions among several participants. Cooperation involves dividing a shared task into separate parts performed by different participants, although these contributions often remain relatively autonomous. Collaboration has a deeper character, as it involves the joint development of a solution, intensive coordination of positions, mutual influence, and the collective construction of meaning. Team interaction combines elements of cooperation and collaboration and also includes additional features: stability of interaction, a shared goal, role structure, distribution of responsibility, and orientation towards a common result⁴⁷.

For teacher education, this distinction is essential. The pre-service computer science teacher should be prepared not simply to participate in group activities, but to engage in joint activities in which each participant acts not beside others, but together with them. This difference defines the professional quality of team interaction. It involves the ability to see a shared goal, relate one's own contribution to the overall logic of the work, accept collectively developed decisions, maintain team dynamics, respond to coordination difficulties, participate in the distribution of roles and responsibilities, and work towards a unified result. In computer science education, this may be seen in the joint design of fragments of a digital course, the collective creation of visual materials, the development of learning algorithms, the modelling of digital cases, and work with shared documents, boards, task-tracking systems or collaborative editing platforms.

The essence of team interaction among pre-service computer science teachers cannot be fully understood without accounting for changes in the teacher's professional role. In a more traditional model, the teacher was often seen as an individual bearer of subject knowledge who independently organises learning, assesses results, and manages the educational process within their own subject responsibility. However, modern educational practice increasingly demonstrates a different logic. The teacher participates in the joint creation of educational programmes and materials, works in networked professional communities, coordinates project activity, integrates digital resources, interacts with colleagues in the development of interdisciplinary tasks, and increasingly acts under conditions of distributed educational

⁴⁷ Brannan L., Parrish C. W., Szatkowski H. D. Team-based learning. *Handbook of research on critical thinking strategies in pre-service learning environments*. Hershey : IGI Global, 2019. P. 89–108. <https://doi.org/10.4018/978-1-5225-7823-9.CH005>

leadership. For this reason, team interaction begins to function not only as a socially desirable quality but as a functionally necessary professional characteristic.

For the pre-service computer science teacher, this necessity is even more evident. A large part of their future professional activity involves participation in processes that cannot be fully carried out according to the logic of isolated individual work. This includes organising digital projects, supporting learners' work in cloud environments, jointly creating learning content, developing materials for blended or distance formats, cooperating within STEM initiatives, working with digital visualisations and dashboards, and participating in the internal digital infrastructure of the educational institution. All of this requires the capacity for team interaction, not as an additional competence, but as a natural condition of professional effectiveness.

Research on digital pedagogical competence also confirms that collaboration and communication are among its basic components. In particular, Tzafilkou et al.⁴⁸ stress that teachers' digital competence includes not only work with technologies, but also the ability to interact, create digital content, and develop professionally. A similar view is expressed by Alom and Ramalingappa⁴⁹, who emphasise that teachers' digital training should include not only technical, but also socio-pedagogical mastery of the digital environment. The findings of Lin et al.⁵⁰ are especially important, as they show that digital pedagogical competence serves as a link between teachers' technical skills and their ability to foster learners' collaboration, communication, and responsible use of technology. These points give grounds for considering team interaction as one manifestation of a broader professional readiness for activity in a digital educational environment.

However, team interaction cannot be reduced only to communicative openness or general goodwill in working with others. Its professional significance lies in its structured character and in its expression in concrete actions. For the pre-service computer science teacher, at least several interconnected dimensions of its manifestation can be distinguished. The first dimension is communicative. It includes the ability to express ideas

⁴⁸ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

⁴⁹ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁵⁰ Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

clearly on digital channels, take part in discussions, ask clarifying questions, give reasoned feedback, respond appropriately to revisions, and maintain the flow of interaction. The second dimension is productive. It concerns the joint creation of a result, which may take the form of a digital document, a visual model, a learning scenario, a course fragment, an interactive exercise, or another educational product. The third dimension is organisational and is connected with role distribution, meeting deadlines, coordinating stages of work, using digital planning tools, and maintaining the integrity of the process. The fourth dimension is reflective, as team interaction requires the ability to analyse one's own contribution, notice coordination difficulties and adjust actions according to the team goal.

It is this multidimensionality that makes team interaction a professionally significant characteristic rather than simply a form of social behaviour. It combines activity-based, communicative, technological, and value-related dimensions. The pre-service computer science teacher should not only be able to work with others, but also understand the logic of joint activity in a digital environment, use the tools that support it, follow the ethics of digital communication, value the collective result, and be ready to take responsibility for the shared process. In this sense, team interaction is both a way of acting and an element of the teacher's professional culture.

The connection between team interaction and the development of educational leadership is also important. In current conditions, leadership is increasingly understood as less of a purely individual managerial trait. Instead, the idea of distributed leadership is becoming more common. In this model, the organisation of joint activity, team support, process facilitation, initiation of change, and coordination of decisions are carried out not only by a formal leader, but by different participants in the educational process depending on the situation. For the pre-service computer science teacher, this perspective is especially important, since they often find themselves at the centre of digital innovations, advise colleagues, help organise the use of digital tools, and act as a mediator between technological possibilities and pedagogical decisions. Thus, team interaction also becomes a basis for developing elements of professional leadership.

The significance of team interaction is further strengthened by its connection with the development of soft skills, which are increasingly seen in modern teacher education as a necessary condition of professional capacity. Communication, collaboration, flexibility, responsibility, the ability to reach agreement, the ability to work with different positions, critical reflection on one's own actions, and support for group work are closely connected with the effectiveness of pedagogical activity in a digital environment. The study

by Yurchenko et al.⁵¹ shows that specially organised team activity can be a factor in the development of soft skills, while the works of Semenog et al.⁵² demonstrate that communication-rich forms of activity can influence more complex personal and professional characteristics. For the pre-service computer science teacher, this means that team interaction has not only instrumental, but also developmental value: it forms qualities that will later influence the style of pedagogical activity, the nature of professional communication, and the ability to work under conditions of educational uncertainty.

In a digital educational environment, team interaction acquires another essential feature: it becomes much more visible for pedagogical analysis. Shared documents, revision histories, comments, visual boards, task calendars, digital traces of participation, and the structure of the created product make it possible to see not only the final result, but also the process of teamwork itself. This opens new opportunities for pedagogical diagnosis, reflection, and purposeful development of the relevant skills. In this respect, the findings of Echeverría et al.⁵³ are indicative. They demonstrated that multimodal dashboards can strengthen reflection on team activity and help the teacher to interpret the process of joint work more effectively. For the training of pre-service computer science teachers, this is especially important, as it enables moving team interaction from general reasoning to more concrete pedagogical observation and assessment.

At the same time, the professionally significant role of team interaction in the training of pre-service computer science teachers does not imply that it is automatically formed through the study of professional disciplines or the use of digital services. On the contrary, the presence of separate group tasks or digital platforms does not guarantee the emergence of teamwork as a stable professional quality. Without specially organised conditions, learners may remain within the limits of formal division of actions, superficial communication, fragmented editing, or situational coordination. For this reason, team interaction should be

⁵¹ Yurchenko A., Drushlyak M., Khvorostina Y., Ostroha M., Ponomarenko V., Semenikhina O. The impact of team competitions on the development of soft skills in youth. *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2024. P. 323–328. <https://doi.org/10.1109/MIPRO60963.2024.10569574>

⁵² Semenog O., Hrona N., Khomych T., Stasiuk T., Yurchenko A., Semenikhina O. Communicative tasks as a means of developing the emotional intelligence of students. *International Journal of Modern Education and Computer Science*, 2024. Vol. 16, No. 4. P. 46–57. <https://doi.org/10.5815/ijmecs.2024.04.04>

⁵³ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

an object of purposeful pedagogical development. It should not be assumed, but designed into the educational process through relevant tasks, criteria, forms of support, and tools for reflection.

The professional significance of team interaction is also evident in its connection to the quality of the computer science teacher's future work. A teacher who has experience of coherent team work in a digital environment will better understand the logic of joint product creation, organise learners' group activity more accurately, work more confidently in collaboration with colleagues, and integrate digital tools into pedagogical practice more effectively. Conversely, the absence of such experience may lead even a technically prepared teacher to reproduce an individualised model of activity that is not sufficiently suitable for the current demands of digital education. For this reason, team interaction should be considered not as an external addition to professional competence, but as one of its working forms.

Thus, team interaction is a professionally significant characteristic of the pre-service computer science teacher, since it reflects their ability to act in a digitally rich, communicatively complex, project-oriented, and networked pedagogical reality. It combines communication, coordination, joint product creation, responsibility for a common result, process facilitation, and reflective understanding of joint activity. For modern professional training, it is important not only to recognise the significance of this characteristic, but also to give it clearer theoretical and methodological form. Therefore, the next logical step is to consider the digital educational environment as a space where team interaction among pre-service computer science teachers can be purposefully and systematically developed under pedagogical guidance.

3.1.3. The Digital Educational Environment as a Space for Developing Team Interaction in Pre-service Computer Science Teachers

In the training of pre-service computer science teachers, the digital educational environment should be viewed not as a set of separate technical tools, but as a specially organised space for professional formation. Within this space, learning content, forms of communication, digital tools, ways of coordinating activity, the logic of joint product creation, and conditions for pedagogical reflection are brought together. This understanding is essential because, in modern teacher education, the environment increasingly determines not only access to resources but also the way learners participate in professionally meaningful practices. For the pre-service computer science teacher, this means that the digital environment is at once an object of mastery, a means of learning, and a model of future professional

reality. For this reason, the issue of developing team interaction cannot be addressed without analysing how the digital educational environment is organised, which forms of work it supports, and which types of professional participation become possible within it^{54,55,56}.

In a broader pedagogical sense, the digital educational environment is not limited to a distance learning platform, a video communication system, or a repository of digital materials. It should be understood as an integrated infrastructure of activity, in which communication channels, collaborative editing services, visualisation tools, coordination instruments, feedback mechanisms, digital artifacts and norms of interaction are combined. For the pre-service computer science teacher, such an environment is especially important because, in later professional practice, they will not simply use it, but will also participate in its construction, adaptation, and pedagogical content development. Accordingly, during professional training, the future teacher should gain experience of working in such an environment, one that not only provides access to learning resources, but also creates conditions for teamwork, distributed responsibility, joint decision-making, and the collective creation of an educational product.

The problem is that, in practice, the digital educational environment is often organised as a set of disconnected services, each of which performs a narrow technical function, but is not always integrated into a pedagogically meaningful logic of interaction. In this case, it mainly supports individualised activity: downloading materials, receiving instructions, submitting completed tasks, and leaving occasional comments. However, this is not enough for developing team interaction. What is needed is an environment in which joint activity is not an incidental element, but one of the basic forms of participation. This means that the digital environment should be designed so that collective discussion, coordination of positions, role distribution, collaborative editing, process visualisation, tracking of contributions, recording of interim decisions, and pedagogical reflection on teamwork become naturally possible.

⁵⁴ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

⁵⁵ Богославський С., Семеніхіна О., Юрченко А. Порівняльний аналіз українських та європейських практик організації цифрового освітнього середовища. *Науковий вісник Південноукраїнського національного педагогічного університету імені К. Д. Ушинського*, 2025. Випуск 2 (151). С. 38–42. <https://doi.org/10.24195/2617-6688-2025-2-6>

⁵⁶ Yurchenko A., Mulesa P., Semenikhina O. Individual educational trajectory building as a successful teacher skill in the digital age. *Pedagogy and Education Management Review*, 2023. Vol. 2. Pp. 64–72. <https://doi.org/10.36690/2733-2039-2023-2-64-72>

For the pre-service computer science teacher, this way of posing the issue is especially important, since a substantial part of their future activity will take place in digitally organised environments. This concerns not only the use of electronic registers or learning management systems, but also work in cloud spaces, collaborative document creation services, digital boards, visual editors, tools for developing learning resources, and instruments for communication and coordination of project activity. This means that, in professional training, the digital environment should be treated not as an addition to traditional learning, but as a natural field of professional formation. The more methodologically well organised it is, the more likely it is that the learner will not only master the tools, but also gain experience of team interaction within them^{57,58}.

A distinctive feature of the digital educational environment as a space for developing team interaction is its ability to make joint activity visible. In the traditional classroom format, a large part of the processes of agreement, clarification, micro-distribution of roles, and current coordination remains unrecorded or is recorded only partly. Digital tools, by contrast, make it possible to see a document's revision history, the sequence of changes, participants' comments, time markers, the structure of a board, the logic of task movement, and the nature of feedback. All this turns team interaction into a more observable and pedagogically analysable process. This is one of the important advantages of the digital environment: it not only supports interaction, but also creates conditions for its awareness, assessment, and purposeful development. A similar logic is confirmed by the study of Echeverría et al.⁵⁹, which showed that multimodal dashboards can strengthen reflection on team activity and make particular aspects of the group process visible.

At the same time, visibility is not the same as effectiveness. The fact that a digital environment allows the team process to be tracked does not yet guarantee that this process will be of high quality. For this reason, the pedagogical design of the environment is decisive. It should include

⁵⁷ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*. 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁵⁸ Soroko N., Shymon O. Teachers' readiness to use digital tools in a STEAM-oriented educational environment. *Educational Analytics of Ukraine*, 2025. № 1. P. 28–42. <https://doi.org/10.32987/2617-8532-2025-1-28-42>

⁵⁹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

such forms of activity organisation that make team interaction internally necessary. If a task can be completed fully on an individual basis, then formally placing learners in a group will not necessarily foster teamwork. By contrast, when a task requires the coordination of approaches, the combination of different contributions, the joint development of a solution, or the collective creation of a digital product, the environment begins to function not as a neutral background, but as a mechanism for organising team activity. In this respect, the findings of Abildinova et al.⁶⁰ and Amemasor et al.⁶¹ are especially indicative. They show convincingly that effective entry into digital practice is linked with active activity, collaborative formats, and systematic methodological support, not only with the technical mastery of tools.

In the training of pre-service computer science teachers, the digital environment adds value by enabling connections between team interaction and professionally relevant content. This means that collaboration can be built not around artificial training exercises, but around tasks that are realistic for future pedagogical practice: developing a fragment of a digital lesson, creating an interactive exercise, building a visual model, preparing a learning case, collectively designing materials for blended learning, and creating instructional or analytical resources. In this case, the digital environment becomes a space in which subject-specific, communication, and organisational skills are formed at the same time. This integration makes it especially productive for modernising the professional training of pre-service computer science teachers.

It is also important that the digital educational environment supports different modes of interaction and therefore creates broader opportunities for developing teamwork than the traditional face-to-face model. The synchronous mode enables quick discussion, immediate clarification, facilitation of the group process, and real-time decision coordination. The asynchronous mode allows working with material at one's own pace, returning to comments, revising specific fragments, making edits after reflection, and supporting a longer cycle of joint product creation. For the pre-service computer science teacher, this experience is extremely important, as their later professional activity will also require the ability to organise and combine both modes. Thus, the digital environment not only

⁶⁰ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

⁶¹ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

expands technical possibilities but also changes the temporal and structural logic of team interaction.

The role of digital visualisation tools in organising team interaction should also be emphasised. For computer science education, visualisation is not an incidental element, but one of the natural ways of organising content, designing the process, and presenting the result. Digital boards, diagrams, mind maps, role tables, task trackers, dashboards, and interactive spaces for joint planning help structure team activity. They allow participants to see not only separate messages or fragments of a document, but also the process's overall logic. For this reason, a visually organised digital environment supports team coordination much more strongly than an environment in which interaction is scattered across unrelated channels. A similar conclusion is consistent with the works of Rudenko et al.^{62,63}, which show that digital visualisation strengthens coordination, understanding, and analytical support for joint activity.

However, for the digital educational environment to become a real space for developing team interaction, it must be not only technologically supported, but also normatively and culturally organised. Teamwork in the digital space requires clear communication rules, understanding of roles, defined ways to coordinate decisions, adherence to the ethics of digital communication, respect for the contributions of other participants, and readiness to work in an open editing mode. Without this, even a well-built technical environment may turn into a space of chaotic or conflict-based interaction. For the pre-service computer science teacher, this is especially significant, since in later practice they will themselves be responsible for creating such a culture of digital interaction in work with learners.

The digital educational environment also has considerable reflective potential. It accumulates digital artifacts that can be treated not only as results of activity, but also as material for further analysis of the team process. Revision history, the structure of discussion, ways of responding to comments, the nature of coordination, the distribution of activity among participants, the trajectory of product creation, the pace of task progress, and changes in the structure of a visual board all open up opportunities for more specific pedagogical reflection. For the pre-service computer science teacher,

⁶² Rudenko Y., Ahadzhyanov-Honsales K., Ahadzhanova S., Batalova A., Diemientiev Y., Semenikhina O. Interactive boards as digital tools in the modern educational process. *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2024. P. 329–333. <https://doi.org/10.1109/MIPRO60963.2024.10569393>

⁶³ Rudenko Y., Zhurba K., Bekh I., Petrenko S., Bobokalo A., Semenikhina O. Using dashboards in the development of students' analytical thinking. *2025 48th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2025. P. 406–411. <https://doi.org/10.1109/MIPRO65660.2025.11131997>

this experience is highly valuable, as it develops the ability to view the digital environment not only as a means to complete a task, but also as a source of data about the process of interaction itself. This is especially important in conditions where modern education increasingly relies on analytical support for the educational process and the interpretation of digital traces of activity⁶⁴.

It should also be noted that the digital educational environment influences various components of team interaction in different ways. The communicative component is supported through synchronous and asynchronous communication channels, commenting mechanisms, and opportunities for rapid feedback. The cooperative-productive component develops through tools for collaborative editing, collective content creation, and structured work on a single digital product. The organisational-project component is formed through tools for visualising stages, role tables, calendars, trackers, digital boards, and various mechanisms for task distribution. Thus, the environment is not a homogeneous background, but a complex system of pedagogically significant resources, each of which can support separate dimensions of teamwork in different ways. For this reason, its analysis is a necessary step in studying team interaction as a component of the professional training of pre-service computer science teachers.

It is no less important that the digital environment creates opportunities for the gradual complication of team interaction. At the initial stage, it can support basic forms of joint discussion, short coordination exercises, or simple collective editing. Later, it enables moving on to more complex tasks that require role distribution, the creation of a multi-component digital product, coordination of standards, joint planning, and reflection on the process. Such gradual development is especially productive in teacher education, as it helps to avoid formalism and ensures learners' gradual movement into more mature forms of teamwork. In the training of pre-service computer science teachers, this is methodologically important because it allows the development of professional skills to be combined with the capacity for team activity in the digital space.

Thus, the digital educational environment should be viewed as a full space for developing team interaction in pre-service computer science teachers. Its pedagogical productivity is determined not by the number of services used, but by how coherently it brings together communication,

⁶⁴ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

joint product creation, coordination of actions, process visualisation, rules of interaction, and reflective support. In this understanding, the digital environment becomes not only a technical resource, but also a space of professional formation, where the pre-service computer science teacher masters ways of acting without which modern pedagogical practice is no longer possible. For this reason, further analysis of team interaction requires a move towards its internal structure, criteria, and indicators of formation.

3.2. Structure, Criteria, and Indicators of Team Interaction Formation in Pre-service Computer Science Teachers

3.2.1. The Structure of Team Interaction in Pre-service Computer Science Teachers

The move towards analysing the structure of team interaction in pre-service computer science teachers is a natural step after clarifying the role of digital transformation in education and the importance of the digital educational environment for teachers' professional formation. If the previous subsections showed that the modern model of training cannot be limited to the individual mastery of professional and digital skills, it is now necessary to define more precisely which components constitute team interaction as a professionally significant characteristic. Without such clarification, it risks remaining a very general concept, useful for declarations but insufficiently suitable for pedagogical design, assessment, and purposeful development.

Research on cooperation, collaboration, digital pedagogical competence, and teacher professional development shows a common idea: effective team interaction is not simply the sum of communication skills or the result of placing people in a group. It has a complex internal organisation and combines activity-based, communicative, organisational and reflective aspects. For this reason, it should be considered as an integrated professional construct. It is expressed in the pre-service computer science teacher's ability to take part in the joint achievement of a goal, coordinate actions with other participants, create a collective result in a digital environment, and adjust their own behaviour according to the logic of teamwork. This approach is consistent with the current understanding of teachers' digital competence as a multidimensional system in which collaboration and communication have an important place^{65,66}.

⁶⁵ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁶⁶ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

The need for structural analysis is especially important in the training of pre-service computer science teachers. In this field, team interaction cannot be reduced to a general readiness to work with others. It is connected with work in cloud environments, the creation of shared digital content, the development of learning materials, the visualisation of ideas, the coordination of stages of a digital project, the facilitation of joint problem-solving, and the use of tools that make each participant's contribution visible. For this reason, the structure of team interaction should reflect not only the psychology of interpersonal cooperation, but also the specific features of digitally mediated pedagogical activity. In this understanding, it should include at least three interrelated dimensions: communication, joint product creation, and process organisation.

It is reasonable to proceed from the view that the structure of team interaction in pre-service computer science teachers includes three main components: communication-facilitation, cooperative-productive, and organisational-project. This structure makes it possible to avoid excessive fragmentation of the phenomenon while still covering the main ways in which it is expressed in a digital educational environment. These components do not exist separately. In the real educational process, they constantly overlap, strengthen one another and can be considered separately only for analytical purposes. However, distinguishing them makes it possible to define further the criteria, indicators and levels of team interaction formation.

The first component is communication-facilitation. Its importance follows from the fact that any team work in a digital environment begins not with product creation, but with the establishment and maintenance of functional interaction among participants. For the pre-service computer science teacher, this component includes the ability to communicate meaningfully in digital channels, express ideas clearly, ask clarifying questions, provide reasoned feedback, respond to the suggestions of others, support discussion and help the team move towards an agreed decision. It is also important that this is not only about general communicative activity, but about the facilitative dimension of interaction. The pre-service computer science teacher should be able not only to take part in a conversation, but also to support the team work process itself: to help structure discussion, notice communication failures, return the team's attention to the shared goal, support the involvement of less active participants and maintain a working atmosphere. In this sense, communication in the structure of team interaction is not a supporting element, but its functional core.

There are specific reasons for including the facilitative aspect within the communication component. In professional practice, the modern computer science teacher often works as an organiser of group activity, a consultant on

the use of digital tools and a coordinator of joint task completion. They should not only be able to communicate themselves, but also create conditions for the productive communication of others. For this reason, the communication component in the structure of team interaction should include the capacity for pedagogically appropriate facilitation. This logic is consistent with the findings of Lin et al.⁶⁷, who show that it is digital pedagogical competence, rather than technical skill alone, that mediates the teacher's ability to organise collaboration and the responsible use of technologies.

The second component is cooperative-productive. Its necessity is determined by the fact that a real team does not limit itself to exchanging views, but works towards creating a shared result. For the pre-service computer science teacher, this result often has a digital form. It may be a fragment of an electronic course, a lesson scenario, an interactive exercise, a set of visual materials, a digital case, a shared document, a learning instruction, a model or another educational product. Accordingly, the cooperative-productive component includes the ability to take part in the collective creation of such a product, coordinate one's own contribution with the contributions of others, and work in a mode of collaborative editing, revision and integration of parts into a coherent structure. It also includes readiness to accept changes suggested by other participants and to move away from a purely individual logic of authorship towards the logic of a collective result.

The productive dimension is precisely the element that distinguishes team interaction from superficial group activity. If joint work does not lead to the creation of an agreed result, it risks remaining at the level of parallel performance of separate actions. For the pre-service computer science teacher, this is especially significant, as their future professional activity involves the constant creation and adaptation of digital educational materials. Therefore, the capacity for collective digital authorship should be considered an important structural component of team interaction. In this respect, the findings of Brannan et al.⁶⁸ are indicative. They stress that team work has the greatest developmental potential when it is oriented towards the joint production of a solution and collective responsibility for the result, rather than towards the mechanical division of tasks.

The third component is organisational-project. It is connected with the fact that team interaction in a digital educational environment requires not only communication and joint product creation, but also the ordering of the activity

⁶⁷ Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

⁶⁸ Brannan L., Parrish C. W., Szatkowski H. D. Team-based learning. *Handbook of research on critical thinking strategies in pre-service learning environments*. Hershey : IGI Global, 2019. P. 89–108. <https://doi.org/10.4018/978-1-5225-7823-9.CH005>

process itself. For the pre-service computer science teacher, this component includes the ability to see the structure of a joint task, distribute roles, plan stages of work, agree on deadlines, use digital coordination tools, monitor the team's progress and, when necessary, adjust the logic of joint activity. In essence, this concerns the project culture of team work. In modern digital education, it has particular importance, since many collective tasks take place under conditions of multi-channel communication, a combination of synchronous and asynchronous forms of participation, the accumulation of digital artefacts and the need to keep in view not only the content, but also the sequence of actions.

The organisational-project component is especially important for computer science education, where the logic of work is often structured, staged and algorithmic. The pre-service computer science teacher should be able to think about team activity not as a chaotic process, but as a process with defined stages, roles, points of agreement and criteria for the readiness of intermediate results. This brings team interaction closer to real professional situations in which the teacher acts not only as a communicator, but also as an organiser of activity. It is in the digital environment that this component becomes especially visible, since digital boards, trackers, calendars, shared tables and other coordination tools make it possible to record and analyse the team work process itself^{69,70}.

Despite this analytical distinction, the three components form an integrated system. The communication-facilitation component makes it possible to coordinate actions and supports the team's shared thinking. The cooperative-productive component gives interaction its substantive focus, that is, the result around which participants' efforts are united. The organisational-project component orders the process itself, makes it manageable and moves team activity into a more mature form. If one of these components is weakly developed, the overall quality of team interaction decreases. For example, active communication without a shared product may fail to turn into real team activity. The presence of a shared product without organisational coordination often leads to a chaotic combination of fragments. A formal project structure without meaningful communication and facilitation does not ensure real coordination among participants. Therefore, the structure of team interaction should be understood as an interdependent system of components.

⁶⁹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁷⁰ Rudenko Y., Zhurba K., Bekh I., Petrenko S., Bobokalo A., Semenikhina O. Using dashboards in the development of students' analytical thinking. *2025 48th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2025. P. 406–411. <https://doi.org/10.1109/MIPRO65660.2025.11131997>

From the standpoint of the professional training of pre-service computer science teachers, this structure has another advantage: it makes it possible to combine general pedagogical and subject-specific logic. On the one hand, communication, collaboration, coordination and joint result creation are universal features of team work. On the other hand, in computer science education these features take on a clear digital form and are connected with specific tools, types of activity and products. This means that the structure of team interaction is not an externally borrowed scheme, but directly corresponds to the specific features of the professional field of the pre-service computer science teacher.

It is also worth taking into account that the structure of team interaction has not only an operational, but also a value-based dimension. Each component involves a certain professional position. The communication-facilitation component is impossible without respect for other participants and readiness to listen and reach agreement. The cooperative-productive component requires acceptance of the logic of shared authorship and readiness to work for a common result, not only to demonstrate one's own contribution. The organisational-project component is based on responsibility, discipline, respect for agreements and an understanding of the importance of coordination for the quality of joint work. Thus, the structure of team interaction includes not only skills, but also a certain type of professional culture that should be formed in the future teacher.

This approach makes it possible to move from an abstract recognition of the importance of team interaction to its operationalisation. Once the structure of the phenomenon has been defined, it becomes possible to describe the criteria and indicators of its formation, and then to build a methodology for its purposeful development within a digital educational environment. For this reason, structural analysis in this section performs not only an explanatory, but also a design function. It creates the basis for the following subsections, where the assessment criteria, levels of formation and methodological principles for developing team interaction in pre-service computer science teachers will be considered.

Thus, the structure of team interaction in pre-service computer science teachers should be viewed as an integrated system of three interrelated components: communication-facilitation, cooperative-productive and organisational-project. This structure most fully reflects the logic of joint activity in a digital educational environment, corresponds to the specific features of computer science teacher education and creates a basis for further defining the criteria and indicators of formation of this professionally significant construct.

3.2.2. Criteria and Indicators of Team Interaction Formation in Pre-service computer science teachers

After clarifying the structure of team interaction, it is logical to move on to defining the criteria and indicators of its formation. This stage gives the theoretical analysis an applied meaning, as it allows a move from a general description of the phenomenon to its pedagogical operationalisation. If team interaction is considered an important component of modernising the professional training of pre-service computer science teachers, then it should be not only conceptually justified, but also suitable for pedagogical observation, assessment and purposeful development. Without criteria and indicators, it remains more of a value-based guideline than a real educational aim.

In pedagogical research, a criterion is usually understood as a general feature on the basis of which it is possible to judge the state or level of formation of a certain quality, while indicators specify this feature through more observable manifestations. In the case of team interaction in pre-service computer science teachers, this distinction is especially important, as the phenomenon itself has a complex, multi-component character and combines communicative, activity-based, organisational and reflective dimensions. For this reason, the criteria should correspond to the structural components, while the indicators should reflect real actions that can be observed in a digital educational environment during joint activity.

Current research on digital pedagogical competence, collaboration and teacher professional development shows an important methodological point: the assessment of complex professional qualities cannot be based only on formal results or only on subjective self-assessment. A combination of different features is needed, reflecting both the content-related side of activity and its process organisation. Therefore, the criteria for the formation of team interaction should be based on the logic of real team work in a digital environment, where not only the final product is important, but also the way it is created, the nature of communication, the organisation of the process, and readiness to coordinate and adjust one's own actions^{71,72}.

Taking into account the structure of team interaction in pre-service computer science teachers, it is reasonable to distinguish three main criteria of its formation:

⁷¹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁷² Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

communication-facilitation, productive-cooperative and organisational-project. This grouping is methodologically justified because it reflects three basic dimensions of team work: maintaining meaningful interaction, creating a shared result and coordinating the process. Each of these criteria has its own set of indicators, but only together do they provide a sufficiently integrated view of the level of team interaction formation as a professionally significant characteristic of the pre-service computer science teacher.

The first criterion is communication-facilitation. It is distinguished because any team work begins with the establishment and maintenance of functional interaction among participants. In a digital environment, this aspect becomes especially important, as communication often takes place through different channels and requires conciseness, precision, timely responses and the ability to preserve the meaningful coherence of discussion. For the pre-service computer science teacher, this criterion reflects the degree of readiness for constructive digital interaction, the ability to support joint discussion, express ideas clearly and in a subject-related way, coordinate positions and create conditions for productive team work. The significance of this criterion is consistent with the findings of Lin et al.⁷³, who show that teachers' digital pedagogical competence is directly connected with their ability to organise collaboration, communication and the responsible use of technologies.

The indicators of the communication-facilitation criterion should include, first of all, the clarity and meaningfulness of statements in digital interaction. This refers to the ability to formulate messages so that they are understandable to other participants, do not create unnecessary uncertainty and support the progress of joint work. Another important indicator is the regularity and appropriateness of participation in discussion. Team interaction cannot be considered fully formed if a participant joins the joint work only occasionally or formally. The next indicator is the ability to ask clarifying questions, as such questions often signal active involvement in the logic of the shared task. No less important is the ability to provide constructive feedback, that is, not simply to assess or comment on the contribution of others, but to help improve the result without damaging the working atmosphere of the team. Another indicator is the ability to support other participants and help include those who are less active. Finally, an essential indicator is the capacity to keep discussion within the shared goal, that is, to perform at least a minimal facilitative function in the team process.

This approach makes it possible to see communication not as a background support for joint work, but as its active driving force. For the pre-service computer

⁷³ Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

science teacher, this is especially important because in their future professional activity they will need not only to take part in team work, but also to organise it for others. Thus, the communication-facilitation criterion reflects not only the current quality of interaction in a learning group, but also potential readiness for pedagogical management of such interaction in later professional practice.

The second criterion is productive-cooperative. Its significance is determined by the fact that team interaction gains professional meaning only when it is directed towards the creation of a shared result. Communication and coordination alone do not yet guarantee team work if participants are not working on a collective product that requires coordination, integration of contributions and shared responsibility for quality. For the pre-service computer science teacher, this criterion is especially important, as their professional activity is largely connected with the creation of digital, textual, visual, methodological and interactive products. For this reason, the ability to work in the mode of shared digital authorship should be considered an important sign of formed team interaction. In this respect, the productive nature of team activity corresponds to the findings of Brannan et al.⁷⁴, who stress that team learning becomes most effective when it is oriented towards collective problem-solving and the production of a unified result.

The indicators of the productive-cooperative criterion should include the degree of involvement in the joint creation of a product. This means not formal presence in a group, but a real contribution to the shared result. An important indicator is the coherence of one's own contribution with the general structure of the product. A participant may be active, but their work may not always be integrated into the logic of the team result. Therefore, participation should be considered productive when one's own actions are related to the task of the whole team. The next indicator is readiness for collaborative editing and revision. In a digital environment, this feature is seen in the extent to which a participant treats collective editing as a natural mechanism for improving the product, rather than as interference in an individual area of work. Another significant indicator is the ability to accept changes suggested by other participants and, when necessary, adjust one's own contribution. A further indicator is connected with the degree of coherence of the created product: the extent to which the result has a unified logic and is not a mechanical sum of disconnected fragments. Finally, the degree of responsibility for the quality of the common result is important, rather than responsibility only for one's own part of the work.

⁷⁴ Brannan L., Parrish C. W., Szatkowski H. D. Team-based learning. *Handbook of research on critical thinking strategies in pre-service learning environments*. Hershey : IGI Global, 2019. P. 89–108. <https://doi.org/10.4018/978-1-5225-7823-9.CH005>

The productive-cooperative criterion is especially important for modernising the professional training of pre-service computer science teachers, as it makes it possible to connect the development of team interaction with the formation of professionally significant subject-related skills. In this case, team work is not separated from professional content, but is realised through it. The creation of a digital product becomes both a means of developing team interaction and a space in which the level of its formation is shown.

The third criterion is organisational-project. It is distinguished because team interaction in a digital educational environment requires not only communication and a shared product, but also the ordering of the activity process. In digital conditions, where different communication channels, forms of participation, time modes and types of tools are combined, the organisation of the process often determines the success of the whole team. For the pre-service computer science teacher, this criterion is extremely important, as it relates to their future ability to design joint activity, distribute roles, see the stages of work and use digital coordination tools. The significance of this criterion is also supported by studies of digital visualisations and analytical tools, which show that the structure and visibility of the process substantially strengthen the quality of team interaction^{75,76}.

The indicators of the organisational-project criterion should include the ability to see the overall structure of a team task. This is shown in understanding which stages the work consists of, which actions are sequential, which can be carried out in parallel and which require prior coordination. An important indicator is readiness to participate in role distribution and to take on defined functions. The ability to meet agreed deadlines and follow the temporal logic of joint activity should also be included. In a digital environment, this is especially significant because joint work often takes place beyond a single synchronous class and requires the maintenance of pace. The next indicator is the use of digital coordination tools: boards, trackers, tables, planners and shared structured documents. This is not simply about technical use of these tools, but about the ability to apply them to organise the team's work. Another significant indicator is the ability to identify organisational difficulties and suggest ways to overcome them. Finally, an important feature is the ability to maintain the

⁷⁵ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁷⁶ Rudenko Y., Zhurba K., Bekh I., Petrenko S., Bobokalo A., Semenikhina O. Using dashboards in the development of students' analytical thinking. *2025 48th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2025. P. 406–411. <https://doi.org/10.1109/MIPRO65660.2025.11131997>

integrity of the process, that is, not to lose sight of the general logic of team activity even when tasks change or roles are redistributed.

The organisational-project criterion is also important because it brings team interaction closer to the logic of real professional activity. In future pedagogical practice, the computer science teacher will not only work in a team, but will often organise the joint activity of others. Therefore, the ability to see the process as a whole, understand the role of coordination tools, manage stages and maintain the structured nature of work is no less important than the ability to communicate well or complete one's own part of the task effectively.

It should be emphasised that each criterion has diagnostic value only in connection with the others. High communicative activity without a real contribution to the shared product does not allow us to speak of formed team interaction. Similarly, a high-quality individual contribution without readiness for coordination and collaborative editing does not yet mean mature cooperation. In the same way, meeting formal deadlines and using coordination tools do not show a high quality of team work if meaningful interaction and shared responsibility for the result are absent. For this reason, assessment of the formation of team interaction should be complex and based on a set of criteria, rather than on separate isolated features.

From a methodological point of view, defining criteria and indicators has another important function. It makes it possible to move towards the development of tools for pedagogical diagnosis. Self-assessment, structured observation, analysis of digital artefacts, study of revision history, interpretation of comments, analysis of the logic of the shared product or the use of visual coordination tools become meaningful only when it is clear in advance which features the researcher or teacher is looking for. In this sense, criteria and indicators are a kind of bridge between the theoretical model and the real educational process. They make it possible to transform team interaction from a general concept into a phenomenon that can be pedagogically observed, analysed and developed.

Thus, the formation of team interaction in pre-service computer science teachers should be assessed according to three interrelated criteria: communication-facilitation, productive-cooperative and organisational-project. The first reflects the quality of meaningful digital communication and the ability to support the group process. The second characterises the level of participation in the joint creation of a result and readiness for collective authorship. The third reveals the ability to order, coordinate and organise team activity as a project. The set of corresponding indicators creates a basis for further defining the levels of team interaction formation, which is the next logical step in the development of this section.

3.2.3. Levels of Team Interaction Formation in Pre-service computer science teachers

After defining the structure of team interaction and justifying the criteria and indicators of its formation, it is logical to move on to describing the levels of development of this professionally significant construct. The level-based approach makes it possible to view team interaction not as a quality that is either present or absent, but as one that develops gradually, passes through certain stages of formation and can become the object of purposeful pedagogical influence. For the professional training of pre-service computer science teachers, this is especially important, since team interaction in a digital educational environment does not arise automatically as a result of group tasks or the use of digital platforms. It requires specially organised experience, reflection, correction and a gradual transition from elementary forms of involvement to more mature, independent and project-structured participation in joint activity.

The level-based description of team interaction formation should rely on the previously defined criteria: communication-facilitation, productive-cooperative and organisational-project. At the same time, it is reasonable to take into account that the development of team interaction does not always proceed in strict synchrony across all these dimensions. In the practice of professional training, there may be situations where a learner shows a relatively good level of digital communication, but is not yet ready for full collective authorship or is not confident enough in organising the team work process. For this reason, the levels of formation should be understood as generalised types of team interaction manifestation, within which some internal unevenness in the development of separate components is possible. However, for pedagogical analysis, it is important to outline the dominant features that make it possible to identify the prevailing level.

Within this study, it is reasonable to distinguish three levels of team interaction formation in pre-service computer science teachers: low, medium and high. This gradation is methodologically justified because, on the one hand, it clearly differentiates the degrees of formation and, on the other hand, does not create excessive fragmentation that would complicate further diagnosis. It is also consistent with the logic of pedagogical observation, where it is important to record not minor differences between similar states, but the qualitative nature of a learner's participation in team work. In addition, the three-level model is sufficiently convenient for describing the dynamics of change during formative influence.

The low level of team interaction formation is characterised primarily by fragmented participation in joint activity. At this level, the pre-service computer

science teacher usually does not show stable readiness to work according to the logic of a team. Their participation in digital interaction is situational or mainly reactive. Communication is often limited to short answers, formal remarks or occasional involvement in discussion without a noticeable influence on the progress of joint work. Such a learner rarely initiates clarification, does not always respond to comments in time, does not show sufficient sensitivity to the needs of other participants and usually does not perform even minimal facilitative functions. In a digital environment, this may be seen in passive observation of the work of others, weak involvement in discussion or participation that is reduced to separate technical actions without deeper content-related engagement.

In the productive-cooperative dimension, the low level is shown in the fact that the participant mainly perceives the shared task as a set of separate individual assignments. Their contribution to the product may be present, but it is not always related to the general logic of the team result. There is often an orientation towards completing only one's own minimum part, without awareness of the need to improve the shared result. The mode of collective editing or shared digital authorship may cause difficulties, discomfort or a hidden tendency to isolate one's own part of the work. Such a learner is reluctant to accept revisions, rarely initiates improvements to the common product and is not always able to see that the team result should be coherent rather than mechanically assembled from disconnected fragments.

In the organisational-project aspect, the low level is expressed in an insufficient ability to see the structure of the team task and to orient oneself in the logic of the shared process. The pre-service computer science teacher may follow separate instructions, but usually does not show enough initiative in planning, does not actively participate in role distribution and does not use digital coordination tools as means of organising work. They may find it difficult to relate their own actions to the stages of the shared process, to meet agreed deadlines or to respond to organisational changes. As a result, their participation often remains dependent on external guidance, while team interaction itself is perceived as something external to the main content of the work.

Thus, the low level of team interaction formation reflects a state in which the pre-service computer science teacher has not yet moved from an individualised model of activity to the real logic of team work. They may use digital tools, complete separate tasks and even participate in group activity, but their participation does not acquire the features of stable, meaningful, responsible and well-organised interaction. For pedagogical training, this means the need for purposeful support, the creation of safe conditions for entering team work and the gradual complication of forms of joint activity.

The medium level of team interaction formation reflects a transitional state in which the pre-service computer science teacher already shows basic readiness to work in a team, but this readiness is not yet fully stable, independent and internally organised. In the communication-facilitation aspect, this is shown through more regular participation in digital discussion, the ability to maintain contact with other participants, provide some meaningful comments, respond to clarifications and become involved in collective work in a more timely way. However, communication at this level does not always perform the function of supporting the process itself. The pre-service computer science teacher may express their own ideas effectively, but may not always know how to help the team overcome misunderstanding, structure discussion or systematically support less active participants. The facilitative component is still developing and is often realised episodically rather than consciously.

In the productive-cooperative dimension, the medium level is characterised by real participation in the creation of a shared result. The learner is no longer limited to formally completing a separate fragment, but to some extent relates their own contribution to the general logic of the product. They are able to work in a mode of collaborative editing, accept some revisions and improve material with regard to team needs. At the same time, such cooperation is not always fully mature. There may still be a tendency to overestimate one's own part of the work, insufficient attention to the coherence of the product or selective readiness to accept changes initiated by others. At this level, there is already an understanding of the value of a shared result, but it does not always become a stable practice of collective digital authorship.

In the organisational-project aspect, the medium level means that the pre-service computer science teacher begins to understand the stages of joint activity, can work according to a previously defined plan, follow a role and deadlines, and use digital coordination tools if the logic of their use has already been set by the teacher or the group. They are able to see the general structure of the task, but do not always initiate its clarification or correction. Their participation in coordination is more executive than organisational. Such a learner can already work in a structured digital environment quite productively, but does not yet fully show the ability to independently support the team process or restructure it in response to difficulties.

The medium level is especially important for pedagogical analysis because it is here that the potential for further development becomes most visible. At this stage, team interaction ceases to be an external requirement for the pre-service computer science teacher. It begins to be perceived as a natural way of achieving a result in a digital environment. At the same time, moving to a high level requires specially organised conditions that support the development of

project independence, facilitative sensitivity, mature shared authorship and responsibility not only for one's own actions, but also for the logic of team work as a whole.

The high level of team interaction formation describes a state in which the pre-service computer science teacher demonstrates stable, conscious and professionally productive readiness for team activity in a digital educational environment. In the communication-facilitation dimension, this is shown in meaningful, timely, constructive and functionally appropriate participation in discussion. Such a learner not only expresses ideas clearly and provides reasoned feedback, but also supports the interaction process itself. They are able to notice communication gaps, help include other participants, support the team in keeping focus on the shared goal, clarify ambiguous decisions and gently facilitate discussion. In a digital environment, this is seen not simply in activity, but in productive communicative presence that really helps the team work better.

In the productive-cooperative aspect, the high level means mature readiness for the joint creation of a digital product. At this level, the pre-service computer science teacher understands the result as collective, not as individually divided. They can integrate their own contribution into the overall structure, suggest changes that improve the coherent product, work in a mode of collective editing without losing responsibility for quality, accept revisions and use them to improve the shared result. For them, shared authorship is not a compromise, but a natural form of professional activity. In a product created with their participation, one can see not a mechanical combination of parts, but real coordination, structure and coherence. This level corresponds most closely to the modern logic of the professional activity of a computer science teacher, who must be able to work in a shared digital space on different types of educational solutions.

In the organisational-project dimension, the high level is shown in the ability to independently see the logic of a shared task, plan stages of work, take part in role distribution, suggest ways of coordination, use digital tools for visualising and managing the process, and adjust the team's activity in response to new circumstances. At this level, the pre-service computer science teacher does not simply follow instructions, but understands team work as an integrated process. They are able to combine attention to the content of the product with attention to the organisation of activity, see the link between the quality of coordination and the quality of the result, maintain the rhythm of joint work and focus not only on completing their own part, but on the success of the team as a whole. This level most clearly indicates readiness for further professional activity in digitally organised education, where the teacher must not only work in a team, but often also be one of those who supports this team work.

The high level of team interaction formation has one more important feature: it combines activity-based capacity with a professional position. Such a pre-service computer science teacher is not only technically able to work with others, but also values team work as a resource for pedagogical quality. They recognise the importance of coordination, shared responsibility, openness to editing, digital ethics and process organisation. This means that, at a high level, team interaction becomes part of professional culture, not only a set of separate skills. It is this integration of the activity-based and value-related dimensions that indicates the maturity of this construct.

The described levels make it possible to see the dynamics of team interaction formation as a gradual transition from fragmented, externally guided and mainly individualised participation to independent, meaningful, responsible and project-structured team work. In the professional training of pre-service computer science teachers, this logic is especially valuable, as it allows not only the current state to be identified, but also the pedagogical conditions for its change to be designed. If the low level mainly requires involvement in the experience of basic interaction, the medium level requires strengthening cooperation, facilitation and responsibility for the shared product, while the high level involves consolidating team interaction as a stable professional way of acting.

The level-based approach also has methodological significance for the further formative stage of the study. It makes it possible to trace positive dynamics of change, identify the components most sensitive to pedagogical influence and specify which pedagogical conditions support the transition from one level to another. In this sense, the levels of formation perform not only a descriptive, but also a predictive function. They make it possible to build the logic of the methodology, select appropriate observation tools and interpret the results of pilot testing not fragmentarily, but within the general dynamics of team interaction development.

Thus, the formation of team interaction in pre-service computer science teachers should be considered through three levels: low, medium and high. The low level reflects mainly fragmented, reactive and weakly organised participation in team work. The medium level characterises basic readiness for interaction, joint product creation and work in a structured digital environment, but still without full independence and maturity. The high level is expressed in a stable capacity for meaningful, responsible, facilitation-sensitive, cooperatively productive and project-organised team activity. This level-based model creates a basis for the further transition to describing the diagnostic tools and the methodology for developing team interaction in pre-service computer science teachers within a digital educational environment.

3.3. Methodology for Developing Team Interaction in Pre-service computer science teachers in a Digital Educational Environment

The justification of the structure of team interaction and the definition of its criteria, indicators and levels of formation create the basis for the next logical step, namely the development of a methodology for its purposeful formation. At this stage, the theoretical model gains a practical dimension. If, in the previous subsections, team interaction was considered as a professionally significant characteristic of the pre-service computer science teacher, it is now necessary to show how this quality can be developed within the real educational process, which pedagogical means support its formation, and how the digital educational environment should be organised so that it functions not only as an instrumental base, but also as a space for professional growth.

Current research in digital pedagogy and teacher professional development consistently stresses that complex professional qualities are not formed through one-off instruction or simple familiarisation with digital services. The approaches that prove effective are those which combine practical activity, collaborative formats, methodological support, gradual complication of tasks and reflection on one's own experience^{77,78}. For the training of pre-service computer science teachers, this conclusion is of fundamental importance. Team interaction cannot be formed only by explaining its importance or by mechanically including learners in group work. It requires such an organisation of the educational process in which joint activity becomes functionally necessary, professionally significant, digitally mediated and pedagogically meaningful.

The methodology for developing team interaction in pre-service computer science teachers should be based on several initial provisions. First, team interaction is considered as an integrated construct that includes communication-facilitation, cooperative-productive and organisational-project components. Therefore, the methodology cannot focus only on developing separate communication skills or only on completing joint tasks. It must cover different aspects of team work. Second, the formation of this quality should take place not outside professional content, but through it. For the pre-service computer science teacher, this means that team interaction should be developed through professionally relevant tasks connected with the creation of digital educational products, the design of learning fragments, the use of visualisation, digital boards, shared documents and coordination services. Third, the methodology

⁷⁷ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

⁷⁸ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

should be organised so that the digital environment performs not an auxiliary, but a structuring function, that is, it determines the way in which learners participate in team activity.

In line with these provisions, the methodology for developing team interaction can be defined as an integrated system of pedagogically organised actions aimed at developing the pre-service computer science teacher's capacity for meaningful digital communication, joint creation of an educational product, coordination of the team process and reflective understanding of joint activity. In this sense, the methodology is not reduced to a set of exercises or a sequence of classes. It includes the aim, principles, content, forms of organisation, digital tools, pedagogical conditions, the logic of activity development and ways of assessing the changes that take place during training.

The aim of the methodology is to develop team interaction in pre-service computer science teachers as a component of their modernised professional training within a digital educational environment. This aim can be specified through several interrelated tasks. The first task is to develop the capacity for constructive digital communication, including the ability to express ideas, support discussion, provide feedback, clarify decisions and perform elements of facilitation. The second task concerns the formation of readiness for the collective creation of a digital educational product, that is, for work in the mode of shared authorship, editing, revision and coordination of the result. The third task is connected with the development of organisational-project skills, including role distribution, planning of stages, use of digital coordination tools and support for the coherence of joint work. The fourth task is to form a reflective attitude towards team activity, when the pre-service computer science teacher begins to understand not only the content of the product, but also the ways of working together, the difficulties of interaction and their own role in the team process.

The methodology is based on a number of principles that define its internal logic. First of all, the principle of professional relevance should be noted. Its essence is that team interaction is developed through tasks that are directly related to the future work of the computer science teacher. These may include developing a fragment of a digital lesson, creating an interactive exercise, preparing a shared visual model, constructing a learning case, creating digital instructions or jointly designing resources for blended learning. As a result, team work is not perceived as an artificially imposed activity, but gains professional meaning. This approach is consistent with current views on effective digital teacher training, which should not be abstract, but embedded in real pedagogical practices⁷⁹.

⁷⁹ Abildinova G., Abykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/feduc.2024.1473766>

The second important principle is the principle of activity-based conditioning. Team interaction is not formed through passive acquisition of knowledge about collaboration. It appears and develops in activity that requires coordination of actions, integration of contributions, joint search for a solution and collective responsibility for the result. For this reason, the methodology should be built around actions, not around information about them. For the pre-service computer science teacher, this means the need to work on tasks that cannot be fully completed in a purely individual mode. The activity-based nature of the methodology is also connected with the fact that, in a digital environment, the learner should not only know how collaboration is organised, but should also actually act according to the logic of such collaboration.

The third principle is gradual complication. Team interaction does not appear at once in a fully mature form. It develops from basic involvement in digital communication to more complex forms of coordination, shared authorship and project organisation of the team process. Therefore, the methodology should provide a gradual transition from relatively simple types of interaction to more complex ones. At the initial stages, these may be tasks that require short discussion, joint clarification or collective structuring of ideas. Later, it is appropriate to move to the joint creation of a digital product, and then to tasks that already require clear role organisation, distribution of functions, coordination of stages and visualisation of the work process. Such gradual development ensures not only increased complexity, but also a lower risk of formal completion of group tasks.

The fourth principle is the functional organisation of the digital environment. For the development of team interaction, what matters is not the set of digital tools itself, but the carefully planned logic of their use. The pre-service computer science teacher should work in an environment where synchronous communication, asynchronous coordination, collaborative editing, process visualisation and coordination of actions are organised not chaotically, but as interconnected parts of a single working space. This is consistent with the view that the quality of the digital educational environment is determined by its systemic character and pedagogical appropriateness, not simply by the presence of technical resources⁸⁰. In methodological terms, this principle means that each digital tool should perform a clearly defined function in team work.

The fifth principle is reflective support. Team interaction becomes a stable professional quality only when participants do not simply complete a joint task, but understand how they interacted, what helped or hindered the achievement

⁸⁰ Шамоня В. Г., Хворостіна Ю. В., Юрченко А. О., Семеніхіна О. В. Використання засобів комп'ютерної візуалізації в освіті: узагальнення наявних практик. *Педагогічна Академія: наукові записки*, 2026. Вип. 28. <https://doi.org/10.5281/zenodo.19645296>

of the result, how roles were distributed, what the logic of communication was and what value the shared product has. In a digital educational environment, reflection has especially favourable conditions, since revision histories, comments, visual boards, digital traces of activity and the structure of the created result can be used as material for analysis. This is consistent with current approaches to understanding team work through the analysis of digital artefacts and analytical tools⁸¹.

The logic of the methodology involves several consecutive stages. At the first, motivational-orientation stage, it is important to develop in pre-service computer science teachers an understanding that team interaction is not a secondary social skill, but part of the structure of modern professional readiness. At this stage, it is useful to actualise experience of joint activity, identify initial views of team work, show its connection with the digital transformation of education and with the professional role of the computer science teacher. At the same time, learners make their first entry into the digital environment of the methodology: the rules of work, the logic of using tools, norms of communication and principles of interaction are clarified.

The second stage can be defined as operational-communication. Its main task is to develop basic ways of digital team interaction. At this stage, special attention is paid to meaningful communication, clarification of tasks, support for digital discussion, mutual commenting and the development of a habit of joint consideration of a problem. The tasks should be relatively compact, but should require real coordination. For example, they may include collectively defining the structure of a future digital product, agreeing on criteria for its quality, jointly presenting an idea visually or creating a concept map on a particular computer science topic. It is at this stage that the basis of the communication-facilitation component is formed.

The third stage is cooperative-productive. Its content lies in the transition from discussion to the joint creation of a digital product. At this stage, pre-service computer science teachers work in collaborative editing environments, collectively develop materials, agree on the format, structure and content of the result, accept revisions and learn to relate their own contribution to the logic of the overall product. It is important that the product is professionally significant. These may be learning materials, digital exercises, lesson scenarios, elements of a distance course, visual instructions or interactive mini-projects.

⁸¹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

This stage most intensively develops the cooperative-productive component of team interaction.

The fourth stage should be defined as organisational-project. Here, team work gains a higher level of structure. Participants not only create a shared product, but also plan stages, distribute roles, use digital boards, calendars, trackers or other coordination tools, monitor progress and adjust their own actions. At this stage, the importance of the organisational-project component increases. The pre-service computer science teacher begins to understand team activity as a managed process, rather than as a spontaneous combination of individual efforts. It is within this stage that team interaction comes closest to the logic of the future professional activity of the teacher, who must organise the joint digital work of others.

The fifth stage is reflective-generalising. Its purpose is to analyse the acquired experience, understand changes, relate one's own participation to the criteria of team interaction and identify individual development dynamics. At this stage, self-assessment, discussion of difficulties, analysis of digital artefacts, examination of revision history and discussion of the logic of the team process are used. It is here that team interaction moves from the level of a completed action to the level of a conscious professional quality. For the pre-service computer science teacher, this has particular value, as they not only experience collaboration, but also begin to see how such experience can later be organised pedagogically in work with learners.

In formative terms, the methodology is implemented through a series of digitally organised training sessions. The training format is justified because it allows attention to be focused not so much on the transmission of knowledge as on the development of ways of acting. In the study, this format was connected with three weekly training sessions based on the use of video communication, messengers, shared documents and digital boards. Such organisation is not accidental. It makes it possible to combine synchronous discussion with asynchronous revision, textual interaction with visualisation, collaborative editing with project coordination. Thus, each tool within the methodology performs not only a technical, but also a pedagogically defined function.

Video conferencing services provide a space for synchronous interaction, rapid coordination of positions and facilitation of the group process. Messengers support short asynchronous communication, clarification of details, reminders and current coordination. Shared documents create conditions for the collective development of a textual or structured product and make it possible to work through commenting, mutual editing and revision. Digital boards perform the function of visualising ideas, planning stages, recording roles, structuring content and coordinating the process. Together, these tools create a functionally

rich digital environment in which team interaction gains concrete, observable and pedagogically manageable forms^{82,83}.

The effectiveness of the methodology is also ensured by a system of pedagogical conditions. First of all, this concerns the professional relevance of tasks. Team interaction is formed much more deeply when learners work on something directly related to their future pedagogical activity. The second condition is the functional organisation of the digital environment, where tools do not duplicate one another chaotically, but form a working system. The third condition is a supportive atmosphere of interaction, in which digital editing, commenting and correction are perceived not as a threat to individual contribution, but as a natural part of joint work. The fourth condition is reflective support, which allows participants to understand the logic of their own interaction. The fifth condition is the gradual complication of tasks, through which team interaction moves from basic forms of communication to more mature forms of shared authorship and project coordination.

An important feature of the methodology is that it is oriented not towards a one-time result, but towards development dynamics. This means that assessment concerns not only the successful completion of a specific task, but also changes in the learner's way of participating in team work. The focus is on whether the learner has begun to communicate more actively, coordinate their own contribution with the contributions of others more effectively, use coordination tools more consciously, and show greater readiness for collaborative editing and reflection. This logic makes it possible to view the methodology as a tool of professional growth, not only as a form of organising a class.

Thus, the methodology for developing team interaction in pre-service computer science teachers in a digital educational environment is an integrated system that combines professionally relevant content, an activity-based foundation, staged organisation, a functionally organised digital environment, a training format, reflective support and an orientation towards development dynamics. Its main feature is that digital tools are used not as an external technological resource, but as a means of the pre-service computer science teacher's real entry into the practice of team-based professional

⁸² Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁸³ Rudenko Y., Ahadzhanov-Honsales K., Ahadzhanova S., Batalova A., Diemientiev Y., Semenikhina O. Interactive boards as digital tools in the modern educational process. *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2024. P. 329–333. <https://doi.org/10.1109/MIPRO60963.2024.10569393>

activity. As a result, team interaction acquires the features not of accidental group activity, but of a purposefully formed component of modernised professional training.

3.4. Organisation of the Pilot Study and Testing the Effectiveness of the Methodology for Developing Team Interaction in Pre-service computer science teachers

The development of a methodology for forming team interaction in pre-service computer science teachers within a digital educational environment required not only theoretical justification, but also an initial empirical check of its practical viability. For this reason, a pilot stage was included in the structure of the study. Its aim was to identify the initial sensitivity of the proposed methodology to changes in the levels of team interaction formation and to check whether the diagnostic tools were suitable for recording such changes. The pilot study does not claim to provide exhaustive statistical proof of effectiveness in all possible conditions. However, it makes it possible to assess the direction of change, clarify the most sensitive components and confirm the methodological appropriateness of the chosen approach.

The empirical base of the pilot study consisted of the results of 26 participants. Indicators were recorded in three areas: digital communication and facilitation, joint content creation, and team project management. For each area, two measurements were carried out: before the implementation of the experimental programme and after its completion. Assessment was conducted on a 4-point scale, where 1 point corresponded to the initial level, 2 points to the basic level, 3 points to the advanced level, and 4 points to the expert level. This scale is suitable for the pilot stage, as it allows a qualitative description of levels to be combined with a quantitative presentation of dynamics. At the same time, because the scale is ordinal, statistical analysis should rely not only on mean values, but also on medians and non-parametric tests.

The assessment was based on a mixed approach. Three data sources were combined: self-assessment, a practical task followed by observation of team work in a digital environment, and analysis of digital artefacts. This structure is consistent with current views on the diagnosis of complex professional qualities, for which neither subjective survey data alone nor external observation alone is sufficient. Self-assessment made it possible to record participants' individual views of their own abilities in digital team work. The practical task in microgroups created conditions for the real manifestation of team interaction. The analysis of artefacts, version histories, chats and the structure of coordination tools made it possible to see the actual nature of interaction, not only declared intentions. This approach is consistent with the view that

assessment of collaboration in a digital environment should take into account both the process and the result of team activity⁸⁴.

Procedurally, the pilot study was organised as a short formative cycle that combined pre-measurement, participation in a series of digitally organised training sessions and repeated assessment after the programme had been completed. The content of the activity was connected with the joint development of educational materials and the planning of a team product in a digital environment. Participants worked in microgroups, using synchronous communication services, shared documents and coordination tools. Such organisation followed the logic of the proposed methodology, according to which team interaction is developed not through information about team work, but through direct experience of such work in the digital space^{85,86}.

For the initial description of the empirical data, means, standard deviations, medians and the proportions of participants who showed growth in indicators were calculated. The analysis showed that, in all three competence areas, after the completion of the programme there was a clear shift in results towards higher levels. In the area of “Communication”, the mean score increased from 2.04 to 3.12 points, that is, by an average of 1.08 points. The median changed from 2 to 3 points. Before the programme, 6 participants were at level 1, 13 at level 2 and 7 at level 3. After the programme, the distribution changed as follows: 5 participants were at level 2, 13 at level 3 and 8 at level 4. This means that, in the communication dimension, there was not merely a slight increase in separate individual scores, but a shift of the whole group from initial-basic manifestations to basic-advanced and advanced-expert ones. Improvement in this indicator was recorded in 24 of the 26 participants, that is, in 92.3%, while in 2 cases the result remained unchanged. No decrease was found.

In the area of “Joint Content Creation”, substantial positive dynamics were also recorded. The mean score increased from 1.77 to 2.85 points, also by 1.08 points. The median changed from 2 to 3 points. Before the formative influence, the initial and basic levels prevailed in the sample: 9 participants had 1 point, 14 had 2 points and only 3 had 3 points. After the programme, the distribution

⁸⁴ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁸⁵ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

⁸⁶ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

became different: 9 participants had 2 points, 12 had 3 points and 5 had 4 points. Thus, the most noticeable change is the disappearance of the initial level and a shift of the centre of the distribution into the advanced level zone. Improvement in this indicator occurred in 24 out of 26 participants, while the value remained unchanged for 2 participants. No deterioration was recorded. In pedagogical terms, this gives grounds to state that work in the mode of shared digital authorship, commenting, coordination of changes and product revision was indeed sensitive to specially organised methodological influence.

The most noticeable dynamics were found in the area of “Project Management”. The mean score increased from 1.77 to 3.04, that is, by 1.27 points, which was the largest increase among the three components studied. The median also changed from 2 to 3 points. Before the experimental programme, 8 participants were at level 1, 16 at level 2 and only 2 at level 3. After the programme, 4 participants were at level 2, 17 at level 3 and 5 at level 4. Thus, here too there was a complete disappearance of the initial level and a shift of the majority of the group to the advanced level. Particularly indicative is the fact that improvement in this competence was recorded in all 26 participants, that is, in 100% of the sample. In pedagogical terms, this is an important result, since the organisational-project component usually requires longer formation than basic digital communication. In this case, even a short pilot cycle showed its high sensitivity to specially organised work with digital boards, task structure, deadlines and role distribution.

The total score, which reflects the integral level of development of the skills studied, was analysed separately. The maximum possible score across the three competences was 12 points. The mean total score increased from 5.58 to 9.00, that is, by 3.42 points. The median changed from 6 to 9 points. An increase in the total result occurred in all 26 participants without exception. Such consistent positive dynamics across all participants indicate that the methodology influenced not only separate isolated actions, but the whole way of participating in digital team work. This is especially important for the professional training of pre-service computer science teachers, where team interaction should be considered as an integrated construct rather than as a set of weakly connected skills.

The Wilcoxon signed-rank test was used to check the statistical significance of the changes. The choice of this test was determined by three circumstances. First, the study involved paired measurements carried out on the same participants before and after the formative influence. Second, the assessment scale was ordinal, not interval. Third, the sample size was relatively small, which also makes non-parametric approaches more appropriate. The obtained results showed statistically significant changes in all three competence areas.

For digital communication and facilitation, the Wilcoxon test gave a value of $p < .001$. Similarly, for joint content creation, $p < .001$ was also recorded. For project management, the changes were also statistically significant at $p < .001$. The integral total score also demonstrated statistically significant positive dynamics at $p < .001$. This makes it possible to state that the identified shifts are unlikely to be random and have a systemic character.

From the point of view of interpreting the results, several important points should be emphasised. First, the positive dynamics in all three areas confirm the practical viability of the proposed methodology. Second, the largest mean increase was recorded in the organisational-project component. This gives grounds to assume that those elements of the methodology which are connected with a clear task structure, process visualisation, role distribution and the use of coordination tools have the most pronounced formative potential. Third, the growth in joint content creation shows that collective digital authorship and work in an open editing mode are not only possible in the training of pre-service computer science teachers, but can also develop quite quickly under conditions of pedagogically well-designed support. Fourth, the improvement in the communication component indicates that digital interaction in a team becomes more constructive, meaningful and facilitation-sensitive even within a short pilot period. This is consistent with studies that stress the importance of active collaborative formats and pedagogical support for developing professional interaction in a digital environment^{87,88}.

At the same time, the results of the pilot study should be interpreted with regard to its format. First, the sample was relatively small, which is typical of a pilot stage, but does not allow broad generalisations. Second, the study did not include a control group, and therefore its conclusions mainly concern internal positive dynamics within the selected group. Third, although the assessment scale is sufficiently convenient for recording levels, it is broad and does not reveal more subtle differences between close states of development. However, even taking these limitations into account, the obtained results have important methodological value. They confirm that team interaction in pre-service computer science teachers is a pedagogically manageable quality, and that its development in a digital educational environment can be quite effective even through a short but coherently organised influence.

⁸⁷ Abildinova G., Abykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

⁸⁸ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

Hus, the pilot study showed positive and statistically significant dynamics in the development of digital team work skills across all three studied areas: digital communication and facilitation, joint content creation and team project management. The most pronounced shifts were found in the organisational-project component, which further confirms the importance of project-structured organisation of joint activity in a digital environment. In general, the obtained empirical data allow the proposed methodology to be considered a promising basis for further, broader research and for practical implementation in the system of modernising the professional training of pre-service computer science teachers.

4. Discussion

The results obtained provide grounds for considering team interaction as a component of the professional training of pre-service computer science teachers that is sensitive to pedagogical influence. First of all, it is important that positive dynamics were recorded in all three areas studied: digital communication and facilitation, joint content creation and team project management. This consistency of changes is substantively important, as it points not to a random improvement in separate skills, but to a broader shift in the way learners participate in digitally mediated team activity. In other words, the proposed methodology influenced not only separate instrumental actions, but also the very logic of team work. This is especially significant for the training of pre-service computer science teachers, where professional readiness can be described less and less through an isolated set of digital skills and is increasingly connected with the ability to act in a shared digital space^{89,90}.

It is noteworthy that the greatest increase was found in team project management. This result does not seem accidental. In the developed methodology, the organisational-project component was most closely connected with clear, visible and manageable elements of the digital environment: role distribution, deadlines, task structure, the use of digital boards, shared documents and coordination tools. While communication and joint product creation may partly develop through almost any group activity, the organisation of joint work usually requires clearer external structuring. For this reason, even a short but well-structured intervention could produce a particularly visible effect here. In

⁸⁹ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁹⁰ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

pedagogical terms, this means that, for the development of team interaction in pre-service computer science teachers, the project-based organisation of the environment has not an auxiliary, but a defining role. This conclusion is consistent with findings on the role of digital visualisation, analytical tools and coordination tools in supporting joint activity and understanding its process^{91,92}.

The growth in indicators related to joint content creation is also important. It gives grounds to state that the mode of collective digital authorship was not only technically accessible to participants, but also pedagogically productive. In this respect, the results are especially significant, since joint creation of a digital product is one of the most professionally relevant forms of activity for the pre-service computer science teacher. This is not simply about the ability to work with a document or a service, but about the ability to integrate one's own contribution into the general structure, accept revisions, improve material according to the team goal and understand the result as shared. The positive dynamics in this area show that involving learners in tasks focused on the collective creation of a product may be one of the most effective mechanisms for developing team interaction. At the same time, this result also has broader significance: it confirms that the digital environment can support not only the exchange of messages or coordination, but also genuinely cooperative and productive activity. This interpretation is broadly consistent with conclusions on the effectiveness of team-oriented learning, where the joint production of a solution and responsibility for the collective result form the core of the learning process⁹³.

The changes in digital communication also deserve separate attention. Although the mean increase here did not exceed the increase in joint content creation, it is substantively important because it concerns the dimension that often remains less visible in quantitative analysis but is fundamental to all team work. Team interaction cannot be productive if its participants are unable to communicate meaningfully, support discussion, clarify tasks, give constructive feedback and gently facilitate the joint process. The fact that, after the programme, the group shifted towards higher levels in the communication

⁹¹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

⁹² Rudenko Y., Zhurba K., Bekh I., Petrenko S., Bobokalo A., Semenikhina O. Using dashboards in the development of students' analytical thinking. *2025 48th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2025. P. 406–411. <https://doi.org/10.1109/MIPRO65660.2025.11131997>

⁹³ Brannan L., Parrish C. W., Szatkowski H. D. Team-based learning. *Handbook of research on critical thinking strategies in pre-service learning environments*. Hershey : IGI Global, 2019. P. 89–108. <https://doi.org/10.4018/978-1-5225-7823-9.CH005>

dimension shows that digital communication within specially organised activity can become more meaningful, less situational and more oriented towards a shared solution. For the training of pre-service computer science teachers, this is especially important, since in their professional activity communication is connected not only with personal participation in a team, but also with the future role of organising and facilitating learners' interaction. This interpretation is consistent with the conclusion that digital pedagogical competence directly mediates the teacher's ability to support collaboration, communication and the responsible use of technologies⁹⁴.

The consistency of positive dynamics across all three areas provides the basis for an important methodological conclusion: team interaction in a digital educational environment should not be developed through the isolated training of separate skills. A more effective organisation of training is one in which communication, joint product creation and process coordination unfold at the same time as different aspects of one activity. This integration was probably one of the factors behind the positive dynamics. If the programme had been built only around training in digital services or only around practising communication skills, its impact would probably have been narrower. In this case, the methodology combined different modes of participation and thus reproduced more realistic conditions of the future professional activity of a computer science teacher. This gives grounds to speak of the pedagogical appropriateness of a comprehensive approach. This conclusion corresponds to studies that stress the effectiveness of practice-oriented, collaborative and stage-based forms of digital teacher training^{95,96}.

Overall, the results obtained are consistent with current research discourse, according to which a teacher's digital competence cannot be reduced to instrumental mastery of technologies. It includes collaboration, communication, content creation, professional development and the organisation of interaction. In this sense, the results of the pilot study support the theoretical assumption that team interaction is not peripheral, but internally connected with the digital pedagogical competence of the pre-service computer science teacher. At the same time, the study specifies this position,

⁹⁴ Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>

⁹⁵ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

⁹⁶ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

as it shows that such interaction can not only be recognised conceptually, but also operationalised through a structure of components, criteria, levels and a development methodology^{97,98}.

The relationship between the obtained results and studies that stress the effectiveness of active, collaborative and practice-oriented formats of teacher professional training is also important. The positive dynamics in the pilot study support the conclusion that specially organised activity in a digital environment, supplemented by a clear structure, a shared task and reflective support, is more productive than simple familiarisation with tools. This is especially visible in the organisational-project component: it is the least likely to develop spontaneously and, at the same time, develops most clearly under conditions where participants are involved in real joint work with a visible structure and distribution of responsibility. Thus, the results support the need to shift the focus in the professional training of pre-service computer science teachers from instructive-demonstrative models to activity-based and collaborative ones^{99,100}.

At the same time, the obtained results allow certain interpretive assumptions to be made. In particular, it may be assumed that the different strength of dynamics across the separate areas is connected not only with the features of the methodology itself, but also with the nature of the corresponding skills. Communication skills partly begin to develop before a specially organised intervention, since learners already have some experience of taking part in digital communication. By contrast, organisational-project skills require greater pedagogical structuring and are therefore more sensitive to purposeful influence. Joint content creation occupies an intermediate position: on the one hand, it relies on existing experience of using digital tools; on the other hand, it requires a move towards a more mature logic of collective authorship. This interpretation does not contradict the empirical data and helps to clarify which components of team interaction require particular attention in the further improvement of the methodology.

⁹⁷ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

⁹⁸ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

⁹⁹ Abildinova G., Abykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

¹⁰⁰ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

Another significant result is that the initial level effectively disappeared in the group across all three areas. In pedagogical terms, this means that even within a short formative cycle it was possible to move participants out of the zone of fragmented, weakly organised and mainly reactive participation in team activity. This does not mean that all participants reached a high level, but it does indicate that the most problematic threshold was overcome, namely the point at which team interaction had not yet become a natural way of acting for the learner. For the system of professional training, this is an important conclusion, since the transition from the initial to the basic level and then to the advanced level is the most critical from the point of view of later professional adaptation. If a learner has already gained experience of structured digital team work, this experience can later be expanded, deepened and transferred into pedagogical practice.

Along with the positive conclusions, the limitations of the study should also be taken into account. First of all, this concerns the pilot nature of the sample. The study involved 26 participants, which is sufficient for an initial check of the practical viability of the methodology, but not for broad generalisations. In addition, the absence of a control group does not make it possible to fully separate the effect of the methodology from the possible influence of other factors, including a general increase in participants' confidence during the work process or the effect of repeated measurement. The 4-point scale itself is also a certain limitation: it is suitable for level-based analysis, but does not capture more subtle internal changes. Finally, part of the assessment relied on self-assessment and therefore does not exclude subjective bias. At the same time, these limitations do not cancel the results, but rather define the boundaries of their interpretation and indicate directions for further research.

In view of this, the next step should be to expand the empirical testing of the methodology. It would be promising to include a control group, increase the sample size, extend the duration of the formative stage and use more detailed scales or combine level-based assessment with the analytics of digital traces. It would also be useful to analyse separately which types of tasks have the greatest effect on the communication, productive or organisational-project components. For the pre-service computer science teacher, this is especially important, as it would allow the development of team interaction to be integrated more precisely into professional disciplines, pedagogical practice and digital modules of the educational programme.

In a broader pedagogical sense, the results of the study allow one more important conclusion to be drawn. Team interaction should not be seen as a by-product of the digitalisation of education. The transition to platforms, services and cloud environments does not in itself guarantee the development

of high-quality collaboration. Moreover, without methodologically meaningful organisation, the digital environment may remain a space for individualised task completion. Only under conditions of specially designed activity does it become a space for developing team interaction. This is exactly what the pilot study showed: the positive dynamics were connected not with the fact of using digital tools as such, but with the fact that these tools were included in the logic of professionally relevant joint tasks, staged coordination and reflective support. This conclusion is consistent with the view that the effectiveness of a digital educational environment is determined by its pedagogical structure and its coherence with the tasks of joint activity, not simply by technological saturation^{101,102,103}.

Thus, the results of the pilot study confirm the promise of the proposed methodology and, at the same time, clarify the conditions of its effectiveness. The data most convincingly show that, for developing team interaction in pre-service computer science teachers, the combination of three elements is decisive: a professionally significant shared product, a functionally organised digital environment and reflectively supported team work. In this combination, team interaction ceases to be only a general requirement of modern education and becomes a real, pedagogically formed component of modernised professional training.

CONCLUSIONS

The study provided grounds for considering team interaction as a substantively significant component of modernising the professional training of pre-service computer science teachers. It showed that the digital transformation of education changes not only the instrumental support of the educational process, but also the professional model of the teacher itself. In current conditions, the pre-service computer science teacher is expected not only to use digital tools, but also to act in an environment of distributed responsibility, joint creation of educational solutions, coordination of team activity and digitally mediated

¹⁰¹ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

¹⁰² Semenikhina O., Yurchenko A., Udovychenko O., Petruk V., Boroznets N., Nekyslykh K. Formation Of Skills To Visualize Of Future Physics Teacher: Results Of The Pedagogical Experiment. *Revista Romaneasca Pentru Educatie Multidimensionala*, 2021. Vol. 13(2). Pp. 476-497. <https://doi.org/10.18662/rrem/13.2/432>

¹⁰³ Yurchenko A. Integration of Project-Based Learning and Digital Visualization for Developing Soft Skills of Future STEM Teachers / O. Semenikhina (Ed.), *STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development*. Canada: Open Science Initiative, 2025. Pp. 135-184. <https://doi.org/10.31110/STEM-CaUk-3.2>

communication. Thus, team interaction should be viewed not as an additional social quality, but as a professional quality closely connected with digital pedagogical competence, the organisation of joint activity and readiness for modern pedagogical practice^{104,105}.

It was clarified that team interaction in pre-service computer science teachers is a complex integrated construct that combines communication-facilitation, cooperative-productive and organisational-project components. This structure reflects not only the general logic of team work, but also the specific features of computer science education, where professional activity is connected with the joint creation of digital products, coordination of actions in a digital environment, visualisation of the process and role distribution. This three-component structure made it possible to move from general discussion of collaboration to a more precise description of what should be developed in pre-service computer science teachers during professional training.

A system of criteria and indicators for team interaction formation was justified. It was determined that the communication-facilitation criterion reflects the quality of digital interaction, the ability to support discussion, provide feedback and facilitate the group process. The productive-cooperative criterion characterises participation in the joint creation of an educational product, readiness for collective authorship, editing and integration of contributions. The organisational-project criterion reveals the ability to see the structure of a shared task, coordinate stages of work, use digital planning tools and support the logic of the team process. On the basis of these criteria, low, medium and high levels of team interaction formation were characterised, which made it possible to describe it not as a static feature, but as one that develops gradually.

It was shown that the digital educational environment should be interpreted not as a set of separate services, but as a specially organised space for developing professionally significant ways of acting. Its pedagogical potential lies in combining communication, collaborative editing, visualisation, coordination and reflective analysis of the team process. The functional organisation of the environment becomes particularly important, as digital tools should perform not chaotic, but clearly defined roles in the structure of team work. This is consistent with current research, which stresses that the effectiveness of digital teacher

¹⁰⁴ Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>

¹⁰⁵ Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

training is determined by the pedagogical logic of using the environment, not only by the technical richness of the tools^{106,107,108,109}.

A methodology for developing team interaction in pre-service computer science teachers within a digital educational environment was developed. It is based on the principles of professional relevance, activity-based conditioning, gradual complication, functional organisation of the digital environment and reflective support. Its specific feature is that team interaction is developed not through explaining its importance, but through learners' direct participation in the joint creation of digital products, coordination of actions, role distribution, digital communication and analysis of their own experience. This approach corresponds to current views on effective formats of teacher training, which rely on active, practice-oriented and collaborative activity^{110,111}.

The results of the pilot study confirmed the promise of the proposed methodology. Positive dynamics were recorded in all three areas: digital communication and facilitation, joint content creation and team project management. The most pronounced shifts were found in the organisational-project component, which indicates the particular sensitivity of team interaction to forms of work in which the digital environment helps to structure the process, distribute roles, visualise stages and support coordination. At the same time, positive changes in the productive-cooperative and communication-facilitation dimensions show that shared digital authorship and meaningful communication can also be developed purposefully within a relatively short formative cycle. This gives grounds to consider team interaction as a pedagogically manageable

¹⁰⁶ Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

¹⁰⁷ Yurchenko A., Khvorostina Yu., Shamonia V., Soroka M., Semenikhina O. Digital Technologies in Teaching Physics: An Analysis of Existing Practices. *2023 45th International Convention on Information, Communication and Electronic Technology, MIPRO 2023 – Proceedings*, 2023. P. 666-671. <https://doi.org/10.23919/MIPRO57284.2023.10159870>

¹⁰⁸ Yurchenko A., Proshkin V., Naboka O., Shamonia V., Semenikhina O. The use of digital technologies in education: the case of physics learning. *International Journal of Research in E-learning*, 2023. Vol. 9(2). Pp. 1–25. <https://doi.org/10.31261/IJREL.2023.9.2.02>

¹⁰⁹ Semenikhina O., Yurchenko A., Udovychenko O., Petruk V., Borozenets N., Nekyslykh K. Formation Of Skills To Visualize Of Future Physics Teacher: Results Of The Pedagogical Experiment. *Revista Romaneasca Pentru Educatie Multidimensionala*, 2021. Vol. 13(2). Pp. 476-497. <https://doi.org/10.18662/rrem/13.2/432>

¹¹⁰ Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/educ.2024.1473766>

¹¹¹ Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/educ.2025.1541031>

quality whose development can and should become a component of the modernised professional training of pre-service computer science teachers.

At the same time, the study also revealed certain limits to the interpretation of the results. The pilot nature of the sample, the absence of a control group and the use of a broad 4-point scale do not allow the conclusions to be extended unreservedly to a wider population. However, even under these conditions, the obtained data are important, as they confirm the practical viability of the methodology, identify the most sensitive components of team interaction and outline prospects for further expansion of the study.

Thus, team interaction should be considered an important component of modernising the professional training of pre-service computer science teachers. Its purposeful development makes it possible to better align teacher training with the requirements of digital education, strengthen the practical orientation of professional formation, develop readiness for the joint creation of educational solutions and prepare future teachers for activity in a digitally organised educational environment.

Practical Recommendations. It is advisable to integrate the development of team interaction into the content of professional disciplines in the training of pre-service computer science teachers, rather than limiting it to separate training episodes. Such integration should take place through the systematic inclusion of shared professionally relevant tasks: developing digital lessons, creating interactive exercises, preparing visual models, jointly designing learning cases, and working with digital resources for blended and distance learning.

The digital educational environment should be built according to the principle of functional organisation. Tools for synchronous communication, collaborative editing, visualisation and coordination should perform clearly defined functions and be included in a single logic of work. In the training of pre-service computer science teachers, it is especially appropriate to combine video conferencing services, shared documents, digital boards and planning tools, since this combination best supports the development of all three components of team interaction.

It is necessary to purposefully develop not only the ability to complete tasks jointly, but also the ability to facilitate the group process. For this purpose, the educational process should include the roles of moderator, coordinator, person responsible for summarising, commentator, organiser of the visual board and similar roles. Such an approach will help pre-service computer science teachers move from the position of team participant to the position of future organiser of learners' team work.

Digital products should be used more widely as the central mechanism for developing team interaction. Team work should focus not on the formal

division of task parts, but on the joint creation of a coherent result that requires coordination, editing, responsibility for quality and collective reflection.

The organisation of team work should be supplemented with systematic reflection. Analysis of revision history, comments, the logic of task progress, participants' roles and difficulties in interaction should become a regular part of training. This will allow pre-service computer science teachers to understand more clearly not only the result, but also the process of team activity itself.

For further research, it is advisable to expand the sample, include a control group, extend the formative stage and refine the assessment tools. It would also be promising to study separately which types of digital tasks most effectively influence the communication-facilitation, cooperative-productive and organisational-project components of team interaction.

SUMMARY

The chapter substantiates the role of team interaction as a component of modernizing the professional training of pre-service computer science teachers in the context of the digital transformation of education. The starting point is the assumption that contemporary teacher training can no longer be reduced to the individual mastery of digital tools, since professional activity is increasingly associated with the collaborative design of educational solutions, coordination of actions, digital communication, facilitation of group processes, and the collective creation of digital products. The aim of the study is to provide a theoretical substantiation of the essence and structure of team interaction of the pre-service computer science teacher, to identify the criteria, indicators, and levels of its development, to design a methodology for fostering this quality in a digital educational environment, and to analyze the results of its pilot implementation. The study employed theoretical analysis of scholarly sources, generalization, modeling, structural and functional analysis, and elements of a pilot formative study using self-assessment, observation, analysis of digital artifacts, and statistical comparison of results before and after the implementation of the methodology. Relevant assessment criteria and indicators were identified, and the development of the studied quality was characterized as low, medium, or high. The developed methodology is based on the principles of professional relevance, activity-based conditioning, gradual complication, functional organization of the digital environment, and reflective support. Its implementation involves engaging pre-service computer science teachers in digitally organized team activities related to the collaborative creation of educational products, coordination of actions, and the use of communication, visualization, and planning tools. The pilot study results demonstrated positive dynamics across all three dimensions, with the most pronounced changes

observed in the organizational and project-based components. It is concluded that team interaction is a pedagogically manageable quality, and its purposeful development enhances alignment between the professional training of the pre-service computer science teacher and the contemporary requirements of digital education.

Bibliography

1. Abildinova G., Abdykerimova E., Assainova A., Mukhtarkyzy K., Abykenova D. Preparing educators for the digital age: Teacher perceptions of active teaching methods and digital integration. *Frontiers in Education*, 2024. Vol. 9. Article 1473766. <https://doi.org/10.3389/feduc.2024.1473766>
2. Alom M. M., Ramalingappa V. Development and validation of a digital literacy scale and the evaluation of post-graduate teacher educators' digital literacy. *International Journal of Information and Education Technology*, 2025. Vol. 15, No. 10. <https://doi.org/10.18178/ijiet.2025.15.10.2421>
3. Amemasor S. K., Oppong S. O., Ghansah B., Benuwa B.-B., Essel D. A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 2025. Vol. 10. Article 1541031. <https://doi.org/10.3389/feduc.2025.1541031>
4. Andersen R., Mørch A., Litherland K. Collaborative learning with block-based programming: Investigating human-centered artificial intelligence in education. *Behaviour & Information Technology*, 2022. <https://doi.org/10.1080/0144929X.2022.2083981>
5. Arefian M. H., Çomoğlu I., Dikilitaş K. Understanding EFL teachers' experiences of ChatGPT-driven collaborative reflective practice through a community of practice lens. *Innovation in Language Learning and Teaching*, 2024. Vol. 20(2). Pp. 318–333. <https://doi.org/10.1080/17501229.2024.2412769>
6. Bhardwaj V., Zhang S., Tan Y., Pandey V. Redefining learning: Student-centered strategies for academic and personal growth. *Frontiers in Education*, 2025. Vol. 10. Article 1518602. <https://doi.org/10.3389/feduc.2025.1518602>
7. Brannan L., Parrish C. W., Szatkowski H. D. Team-based learning. *Handbook of research on critical thinking strategies in pre-service learning environments*. Hershey : IGI Global, 2019. P. 89–108. <https://doi.org/10.4018/978-1-5225-7823-9.CH005>
8. Cohn C., Snyder C., Fonteles J., Montenegro J., Biswas G. A multimodal approach to support teacher, researcher and AI collaboration in STEM+C learning environments. *British Journal of Educational Technology*, 2024. Vol.56, Is. 2. Pp. 595-620. <https://doi.org/10.1111/bjet.13518>
9. Dahri N. A., Yahaya N., Al-Rahmi W. M., Noman H., Alblehai F., Kamin Y., Soomro R. B., Shutaleva A., Al-Adwan A. S. Investigating the

motivating factors that influence the adoption of blended learning for teachers' professional development. *Heliyon*, 2024. Vol. 10, № 15. Article e34900. <https://doi.org/10.1016/j.heliyon.2024.e34900>

10. Diab A.-K., Green E. Cultivating resilience and success: Support systems for novice teachers in diverse contexts. *Education Sciences*, 2024. Vol. 14, № 7. Article 711. <https://doi.org/10.3390/educsci14070711>

11. Echeverría V., Yan L., Zhao L., Abel S., Alfredo R., Dix S., Jaggard H., Wotherspoon R., Osborne A., Buckingham Shum S., Gašević D., Martínez-Maldonado R. TeamSlides: A multimodal teamwork analytics dashboard for teacher-guided reflection in a physical learning space. *Proceedings of the 14th International Learning Analytics and Knowledge Conference*. New York : ACM, 2024. <https://doi.org/10.1145/3636555.3636857>

12. Fitrah M., Sofroniou A., Setiawan C., Widiastuti, Yarmanetti, N., Sari Jaya M. P., Panuntun J. G., Arfaton A., Beteno S., Susianti I. The impact of integrated project-based learning and flipped classroom on students' computational thinking skills: Embedded mixed methods. *Education Sciences*, 2025. Vol. 15, № 4. Article 448. <https://doi.org/10.3390/educsci15040448>

13. García-Delgado M. Á., Rodríguez-Cano S., Delgado-Benito V., di Giusto-Valle C. Digital teaching competence among teachers of different educational stages in Spain. *Education Sciences*, 2023. Vol. 13, No. 6. Article 581. <https://doi.org/10.3390/educsci13060581>

14. Ghazali M., Makrakis V., Kostoulas-Makrakis N., Yakob N., Rashid R. A. A., Othman W., Fitriyanto N. Predicting teacher's information and communication technology-enabled education for sustainability self-efficacy. *Sustainability*, 2024. Vol. 16, № 13. Article 5323. <https://doi.org/10.3390/su16135323>

15. Halawa S., Lin T.-C., Hsu Y.-S. Exploring instructional design in K-12 STEM education: A systematic literature review. *International Journal of STEM Education*, 2024. Vol. 11. Article 43. <https://doi.org/10.1186/s40594-024-00503-5>

16. Hodges C. D., Barbour M., Pratt K. The persistent deficit: Historical gaps in the preparation of K-12 educators for digital teaching. *Journal of Online Learning Research*, 2026. Vol. 12, No 1. Pp. 169-193. <https://doi.org/10.70725/361467zxvzis>

17. Jetzinger F., Baumer S., Michaeli T. Artificial intelligence in compulsory K-12 computer science classrooms: A scalable professional development offer for computer science teachers. *Proceedings of the 55th ACM Technical Symposium on Computer Science Education*, 2024. Vol. 1. P. 1461–1467. <https://doi.org/10.1145/3626252.3630782>

18. Khasawneh Y. J. A., Alsarayreh R., Al Ajlouni A. A., Eyadat H., Ayasrah M., Khasawneh M. An examination of teacher collaboration in professional learning communities and collaborative teaching practices. *Journal of Education and e-Learning Research*, 2023. Vol. 10, № 3. P. 446–452. <https://doi.org/10.20448/jeelr.v10i3.4841>
19. Krishna L., Pisupati A., Teo K. J. H., Teo M. Y. K., Quek C., Chua K. Z. Y., Venktaramana V., Raveendran V., Singh H., Wong S. L. C., Ng V. W. W., Ting O., Loh E. K. Y., Yeoh T. T., Owyong J. L. J., Ong E., Phua G., Hill R., Mason S., Ong S. Y. K. Professional identity formation amongst peer-mentors in a research-based mentoring programme. *BMC Medical Education*, 2023. Vol. 23. Article 764. <https://doi.org/10.1186/s12909-023-04718-y>
20. Kuznetsova M., Gura D., Vorona-Slivinskaya L. Virtual team building in an intelligent collaborative learning environment. *Journal of Information Technology Education: Research*, 2023. Vol. 22. P. 495–517. <https://doi.org/10.28945/5089>
21. Lavado-Anguera S., Velasco-Quintana P.-J., Terrón-López M. Project-based learning (PBL) as an experiential pedagogical methodology in engineering education: A review of the literature. *Education Sciences*. 2024. Vol. 14, № 6. Article 617. <https://doi.org/10.3390/educsci14060617>
22. Lin R., Yang J., Jiang F., Li J. Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China. *Education and Information Technologies*, 2022. Vol. 27. P. 10537–10557. <https://doi.org/10.1007/s10639-022-11274-3>
23. Meletiou-Mavrotheris M., Paparistodemou E. Sustaining teacher professional learning in STEM: Lessons learned from an 18-year-long journey into TPACK-guided professional development. *Education Sciences*, 2024. Vol. 14, № 4. Article 402. <https://doi.org/10.3390/educsci14040402>
24. Norhagen S. L., Krumsvik R., Røkenes F. Developing professional digital competence in Norwegian teacher education: A scoping review. *Frontiers in Education*, 2024. Vol. 9. Article 1363529. <https://doi.org/10.3389/educ.2024.1363529>
25. Paolucci C., Vancini S., Bex R. T., Cavanaugh C., Salama C. D., de Araujo Z. A review of learning analytics opportunities and challenges for K-12 education. *Heliyon*, 2024. Vol. 10, № 4. Article e25767. <https://doi.org/10.1016/j.heliyon.2024.e25767>
26. Revina S., Pramana R., Bjork C., Suryadarma D. Replacing the old with the new: Long-term issues of teacher professional development reforms in Indonesia. *Asian Education and Development Studies*, 2023. Vol. 12, № 4/5. P. 257–274. <https://doi.org/10.1108/AEDS-12-2022-0148>

27. Rudenko Y., Ahadzhanov-Honsales K., Ahadzhanova S., Batalova A., Diemientiev Y., Semenikhina O. Interactive boards as digital tools in the modern educational process. *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2024. P. 329–333. <https://doi.org/10.1109/MIPRO60963.2024.10569393>
28. Rudenko Y., Zhurba K., Bekh I., Petrenko S., Bobokalo A., Semenikhina O. Using dashboards in the development of students' analytical thinking. *2025 48th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2025. P. 406–411. <https://doi.org/10.1109/MIPRO65660.2025.11131997>
29. Rusmin L., Misrahayu Y., Pongpalilu F., Radiansyah R., Dwiyanto D. Critical thinking and problem-solving skills in the 21st century. *Journal of Social Science*, 2024. Vol. 5, № 3. <https://doi.org/10.59613/svhy3576>
30. Semenikhina O., Yurchenko A., Udovychenko O., Petruk V., Borozenets N., Nekyslykh K. Formation Of Skills To Visualize Of Future Physics Teacher: Results Of The Pedagogical Experiment. *Revista Romaneasca Pentru Educatie Multidimensionala*, 2021. Vol. 13(2). Pp. 476–497. <https://doi.org/10.18662/rrem/13.2/432>
31. Semenog O., Hrona N., Khomych T., Stasiuk T., Yurchenko A., Semenikhina O. Communicative tasks as a means of developing the emotional intelligence of students. *International Journal of Modern Education and Computer Science*, 2024. Vol. 16, No. 4. P. 46–57. <https://doi.org/10.5815/ijmeccs.2024.04.04>
32. Shal T., Ghamrawi N., Abu-Tineh A. M., Al-Shaboul Y. M., Sellami A. Teacher leadership and virtual communities: Unpacking teacher agency and distributed leadership. *Education and Information Technologies*, 2024. Vol. 29. P. 6037–6064. <https://doi.org/10.1007/s10639-023-12446-5>
33. Soroko N., Shymon O. Teachers' readiness to use digital tools in a STEAM-oriented educational environment. *Educational Analytics of Ukraine*, 2025. № 1. P. 28–42. <https://doi.org/10.32987/2617-8532-2025-1-28-42>
34. Tanveer M., Mildestvedt T., Skjærseth I. G., Arntzen H. H., Kenne E., Bonnevier A., Stenfors T., Kvernenes M. Peer teaching in undergraduate medical education: What are the learning outputs for the student-teachers? A systematic review. *Advances in Medical Education and Practice*, 2023. Vol. 14. P. 723–739. <https://doi.org/10.2147/AMEP.S401766>
35. Theodorio A. O. Examining the support required by educators for successful technology integration in teacher professional development program. *Cogent Education*, 2024. Vol. 11, № 1. Article 2298607. <https://doi.org/10.1080/2331186X.2023.2298607>
36. Treve M. Comparative analysis of teacher-centered and student-centered learning in the context of higher education: A co-word analysis. *Iberoamerican*

Journal of Science Measurement and Communication, 2024. Vol. 4, № 1. Article 117. <https://doi.org/10.47909/ijsmc.117>

37. Tzafilkou K., Perifanou M. A., Economides A. A. Assessing teachers' digital competence in primary and secondary education: Applying a new instrument to integrate pedagogical and professional elements for digital education. *Education and Information Technologies*, 2023. Vol. 28. P. 10551–10583. <https://doi.org/10.1007/s10639-023-11848-9>

38. Yadav A., Connolly C., Berges M., Chytas C., Franklin C., Hijón-Neira R., Macann V., Margulieux L. E., Ottenbreit-Leftwich A. T., Warner J. R. A review of international models of computer science teacher education. *ITiCSE-WGR*, 2022. <https://doi.org/10.1145/3571785.3574123>

39. Ye H., Liang B., Ng O.-L., Chai C. S. Integration of computational thinking in K-12 mathematics education: A systematic review on CT-based mathematics instruction and student learning. *International Journal of STEM Education*, 2023. Vol. 10. Article 3. <https://doi.org/10.1186/s40594-023-00396-w>

40. Yim I. H. Y., Su J. Artificial intelligence (AI) learning tools in K-12 education: A scoping review. *Journal of Computers in Education*, 2024. Vol. 12, p. 93–131. <https://doi.org/10.1007/s40692-023-00304-9>

41. Yurchenko A. Integration of Project-Based Learning and Digital Visualization for Developing Soft Skills of Future STEM Teachers / O. Semenikhina (Ed.), *STEM Education in Canada and Ukraine: Transformations, Innovations, and Pathways for Sustainable Development*. Canada: Open Science Initiative, 2025. Pp. 135-184. <https://doi.org/10.31110/STEM-CaUk-3.2>

42. Yurchenko A., Drushlyak M., Khvorostina Y., Ostroha M., Ponomarenko V., Semenikhina O. The impact of team competitions on the development of soft skills in youth. *2024 47th MIPRO ICT and Electronics Convention (MIPRO)*. IEEE, 2024. P. 323–328. <https://doi.org/10.1109/MIPRO60963.2024.10569574>

43. Yurchenko A., Khvorostina Yu., Shamonia V., Soroka M., Semenikhina O. Digital Technologies in Teaching Physics: An Analysis of Existing Practices. *2023 45th International Convention on Information, Communication and Electronic Technology, MIPRO 2023 – Proceedings*, 2023. P. 666-671. <https://doi.org/10.23919/MIPRO57284.2023.10159870>

44. Yurchenko A., Mulesa P., Semenikhina O. Individual educational trajectory building as a successful teacher skill in the digital age. *Pedagogy and Education Management Review*, 2023. Vol. 2. Pp. 64–72. <https://doi.org/10.36690/2733-2039-2023-2-64-72>

45. Yurchenko A., Proshkin V., Naboka O., Shamonia V., Semenikhina O. The use of digital technologies in education: the case of physics learning.

International Journal of Research in E-learning, 2023. Vol. 9(2). Pp. 1–25. <https://doi.org/10.31261/IJREL.2023.9.2.02>

46. Zarestky J., Bigler M., Brazile M., Lopes T., Bangerth W. Reflective writing supports metacognition and self-regulation in graduate computational science and engineering. *Computers and Education Open*, 2022. Vol. 3. Article 100085. <https://doi.org/10.1016/j.caeo.2022.100085>

47. Zhang X., Zhang B., Zhang F. Student-centered case-based teaching and online–offline case discussion in postgraduate courses of computer science. *International Journal of Educational Technology in Higher Education*, 2023. Vol. 20. Article 6. <https://doi.org/10.1186/s41239-022-00374-2>

48. Zhou X.-J., Shu L., Xu Z., Padrón Y. N. The effect of professional development on in-service STEM teachers' self-efficacy: A meta-analysis of experimental studies. *International Journal of STEM Education*, 2023. Vol. 10. Article 37. <https://doi.org/10.1186/s40594-023-00422-x>

49. Богославський С., Семеніхіна О., Юрченко А. Порівняльний аналіз українських та європейських практик організації цифрового освітнього середовища. *Науковий вісник Південноукраїнського національного педагогічного університету імені К. Д. Ушинського*, 2025. Випуск 2 (151). С. 38-42. <https://doi.org/10.24195/2617-6688-2025-2-6>

50. Шамо́ня В. Г., Хворості́на Ю. В., Юрченко А. О., Семеніхі́на О. В. Використання засобів комп'ютерної візуалізації в освіті: узагальнення наявних практик. *Педагогічна Академія: наукові записки*, 2026. Вип. 28. <https://doi.org/10.5281/zenodo.19645296>

51. Юрченко А., Момот Р., Острога М., Семеніхіна О. Візуалізація знань засобами вебтехнологій у формуванні критичного мислення майбутніх учителів інформатики. *Фізико-математична освіта*, 2025. Том 40, №5. С. 80-88. <https://doi.org/10.31110/fmo2025.v40i5-11>

52. Юрченко А., Момот Р., Семеніхіна О. Про розвиток інформаційно-цифрової культури вчителів з використанням комп'ютерної візуалізації. *Освіта. Інноватика. Практика*, 2024. Том 12, № 6. С. 93-99. <https://doi.org/10.31110/2616-650X-vol12i6-014>

53. Юрченко А., Різник В., Шамо́ня В., Семеніхі́на О. Взаємні синергійні впливи візуального підходу та SMART-освіти. *Освітологічний дискурс*, 2025. Том 49, №2. С. 6–14. <https://doi.org/10.28925/2312-5829/2025.2.1>

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