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Original Article

Digital culture of future preschool teachers based on neurotechnologies: bibliometric analysis of the literature

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ABSTRACT

The research focuses on preparing preschool educators to use neurotechnologies for personalized child development in the context of educational digitalization. The research aims to conduct bibliometric mapping of the scientific landscape in the field of digital culture formation among future preschool educators based on neurotechnologies for the period 1975-2025, using metadata extracted from 12,879 journal articles indexed in the Web of Science database following PRISMA guidelines. The study examines publication growth dynamics, author productivity, as well as social, intellectual, and conceptual structures. Research on digital culture formation among future preschool educators based on neurotechnologies: (a) demonstrates sustained growth in recent years, particularly in 2020-2025; (b) is published in journals such as "Education and Educational Research," "Linguistics," and "Interdisciplinary Applications in Computer Science"; (c) is conducted by scholars from various geographical regions, with Spain, the USA, and China as leading contributors; (d) relies on a fragmented research community consisting of two research groups with minimal interaction between them; (e) is interdisciplinary in nature and results from the integration of research conducted in education, linguistics, computer science, medicine, and psychology; (f) conceptual analysis revealed that the research field on digital culture formation among preschool educators based on neurotechnologies is only in its initial stage of development. The results of the bibliometric analysis will create a conceptual framework for developing an innovative model for training pedagogical personnel capable of effectively integrating neurotechnologies into the educational practice of preschool institutions in Kazakhstan.

Keywords: Digital culture, Digital literacy, Digital competence, Future preschool teacher, Pre-service early childhood educator, Neurotechnology

Introduction

The digital transformation of modern society encompasses all spheres of human activity, including the educational space, and requires substantial modernisation of pedagogical systems at all levels [1-3]. This process naturally extends to the preschool education system, which is characterised by the intensive implementation of information and communication technologies, artificial intelligence and automated management systems for the educational process: interactive educational environments are being created, multimedia technologies are being used to develop children's cognitive abilities , and electronic document management systems and digital monitoring of pupils' educational achievements are being introduced [4-6]. In the context of these changes, the state education policy of Kazakhstan actualises the use of digital

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educational resources as an integral component of the modern educational environment, necessitating a revision of approaches to the professional training of preschool education teaching staff [7].

The implementation of advanced technologies in educational practice faces serious obstacles, as the integration of neuropedagogical approaches represents a qualitatively new and under-researched direction not only in Kazakhstan's educational science, but is also insufficiently conceptualised in the professional consciousness of the pedagogical community, as a result of which educators lack theoretical knowledge about the neurobiological mechanisms of learning and practical skills in applying neurotechnologies in the educational process [8-10]. This deficit manifests itself in teachers' inability to work with interactive educational platforms, use digital tools to create developmental content, analyse data on pupils' educational achievements and apply adaptive educational technologies [11].

The complexity of the situation is exacerbated by the fact that the psychological and neurocognitive characteristics of representatives of Generations Z and Alpha (are characterised by clip thinking, high speed of attention switching, predominance of visual-figurative perception of information and intuitive command of digital technologies, forming qualitatively new requirements for the methodological arsenal of preschool educators [12, 13]. Neuropsychological research records changes in the structure of cognitive processes in modern preschool children: an increase in working memory capacity with a simultaneous decrease in the stability of voluntary attention, predominance of parallel information processing over sequential [14, 15].

The modern paradigm of personalised education further actualises the identified problem, as it presupposes the creation of individual educational trajectories based on objective data about cognitive processes, neuropsychological characteristics and potential capabilities of each child [16]. The implementation of individualisation of education requires teachers to be able to interpret the results of neuropsychological diagnostics, design developmental programmes taking into account dominant channels of perception, peculiarities of functional brain asymmetry and individual pace of neurocognitive maturation [17, 18].

The analysed trends form the main *research problem*: the existing system of training teaching staff for preschool education does not ensure the formation of digital culture necessary for the effective use of neurotechnologies in professional activities, hindering the implementation of a personalised approach to the development of preschool children in the context of digital transformation of education [19-21].

For a scientifically grounded solution to the identified problem, *bibliometric analysis* of scientific publications in the field of forming a digital culture of preschool educators based on neurotechnologies will make it possible to identify current trends and research directions, determine the most productive authors and scientific schools working on this issue, analyse the dynamics of publication activity and the geography of research. The results of the bibliometric analysis will provide a scientifically grounded definition of promising research directions, identification of under-researched aspects of the problem and formation of a conceptual basis for developing an innovative model for training teaching staff capable of effectively integrating neurotechnologies into the educational practice of preschool organisations.

Literature review

Conceptual understanding of teacher's digital culture

Contemporary research conceptualizes teacher's digital culture as a complex integrative formation that extends beyond mere technical proficiency with digital tools to encompass value-semantic orientations, ethical principles, and methodological approaches to organizing education in digital environments [22, 23]. This understanding is grounded in constructivist learning, connectivism, and social construction of knowledge theories [24], which support a transition from traditional transmissive education models to interactive paradigms based on collaborative knowledge creation. The concept has evolved historically from basic computer skills to a comprehensive professional identity characteristic. Contemporary scholarship [25] identifies three developmental levels: basic (fundamental digital tools), advanced (creating original educational content), and expert (integrating digital technologies into pedagogical conception), enabling differentiated competence formation approaches.

Digital culture of preschool education teachers

The formation of digital culture in preschool teachers must account for young learners' developmental characteristics. The cognitive component includes understanding developmental patterns in children aged 3-7, knowledge of digital technologies' possibilities and limitations for this age group, and ability to critically analyze educational applications from a developmental perspective [26].

The technological component encompasses specialized skills with interactive whiteboards, tablets, educational robots, and augmented reality. Effectiveness depends primarily on teachers' ability to integrate these tools into play activities rather than technical complexity [27]. Creating multimedia stories, interactive games, and virtual excursions requires both technical skills and understanding of narrative pedagogy and gamification principles. The communicative component [28] is particularly significant for parent interaction, as digital platforms enable transparent educational environments where parents can track developmental progress and receive personalized recommendations. The reflective-evaluative component [29] involves systematic analysis of digital technologies' impact on cognitive, emotional, social, and physical development, allowing teachers to adjust usage intensity according to individual needs.

Neurotechnologies in preschool education

Modern neurotechnologies are classified by invasiveness and educational function [30-32]. Non-invasive methods like electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) safely investigate brain activity in preschool children. EEG registers brain rhythm changes associated with attention, memory, and linguistic information processing, while portable equipment enables naturalistic kindergarten research. fNIRS offers high movement tolerance—critical for preschool children—and enables studying prefrontal cortex activation during executive function tasks [33]. Eye-tracking technologies [34, 35] objectively assess attention and visual perception, revealing which educational elements attract attention, focus duration, and visual search strategies, facilitating optimized material design. Neurofeedback technologies [36-39] enable children to consciously influence brain activity through operant conditioning. Gaming protocols adapted for ages 4-6 use visual and auditory stimuli responsive to brain activity states, developing self-regulation, attention concentration, and behavioral correction.

Professional development through neurotechnologies

Integrating neurotechnologies into teacher training [40] develops competences rooted in neurobiological understanding of learning and development, enabling evidence-based decision-making. Training modules on neuroscience fundamentals cultivate scientific understanding of attention, memory, executive functions, and emotional regulation. Neurotechnologies expand pedagogical assessment tools beyond traditional observation and testing. Teachers skilled in interpreting neurophysiological data [41] can more accurately plan individual trajectories and adjust strategies. EEG neurofeedback for teachers' own emotional regulation training enhances stress resilience and attention concentration. Research demonstrates that such training improves behavior management effectiveness and creates positive educational atmospheres [42-47].

Psychological and pedagogical implementation considerations

Applying neurotechnologies in preschool education requires understanding developmental peculiarities and technology interaction specifics. Researchers emphasize [48] considering sensitive periods when planning interventions. Preschool age features intensive prefrontal cortex development [49], creating opportunities for purposeful executive function development through neurofeedback. Emotional safety demands particular attention [50]. Children may experience anxiety with EEG equipment, perceiving electrodes as medical instruments. Successful protocols incorporate gaming elements, presenting headsets as "space helmets" or "superhero crowns" to reduce anxiety and increase motivation. Individualizing education based on neurotechnological data requires considering cognitive, emotional, and social development. Brain activity pattern analysis [51] reveals preferred perception modalities, optimal attention duration, and effective motivation strategies, enabling personalized programs aligned with each child's neurocognitive profile.

Materials and Methods

Research purpose and objectives

The purpose of this research is bibliometric mapping of the scientific landscape in the field of forming the digital culture of future preschool organisation teachers based on neurotechnologies for the period 1975-2025, with the purpose of systematising accumulated scientific knowledge and determining promising directions for further research.

To achieve the stated purpose, the following objectives were defined:

1. To analyse the dynamics of publication activity in the field of forming the digital culture of future preschool organisation teachers based on neurotechnologies over a fifty years period (1975-2025) in order to identify the main stages of development of the scientific direction and determine the trajectory of its growth.
2. To identify the most productive sources of publications, leading researchers and countries that have made a substantial contribution to the formation of scientific knowledge about the application of neurotechnologies in developing digital culture of preschool education teachers.
3. To construct maps of scientific collaboration networks between researchers, institutions and countries in order to determine centres of scientific expertise and models of international cooperation in the field under study.
4. To establish interdisciplinary connections and scientific disciplines that constitute the theoretical and methodological foundation of research into the formation of the digital culture of future preschool organisation teachers through neurotechnologies.
5. To identify and systematise the main thematic blocks of research reflecting the conceptual structure of the scientific field and the evolution of key directions in studying the processes of developing the digital culture of preschool education teachers based on neurotechnological approaches.

Methodology

The formation of the research data array was carried out on the basis of an analysis of publications indexed in the Web of Science (WoS) database for the period from 1975 to 2025. The use of the Web of Science platform as the main source of bibliometric information is determined by a combination of methodological advantages of this system. The database is characterised by significant depth of retrospective coverage, providing the opportunity to conduct long-term analysis of the evolution of a

scientific direction. The interdisciplinary indexing principle includes more than 22,778 peer-reviewed scientific journals representing various areas of knowledge, which is important for researching the interdisciplinary problematic of forming teachers' digital culture based on neurotechnologies.

The strict criteria for quality selection of sources for indexing in WoS guarantee a high scientific level of the publications analysed and ensure the representativeness of the sample. The developed analytical system for assessing citation enables the determination of the scientific influence and academic significance of research in the field under consideration. The structured organisation of metadata in the WoS database substantially simplifies the procedures of searching, filtering and systematising relevant scientific literature [52]. A detailed methodological scheme for conducting the bibliometric study is presented in **Figure 1**.

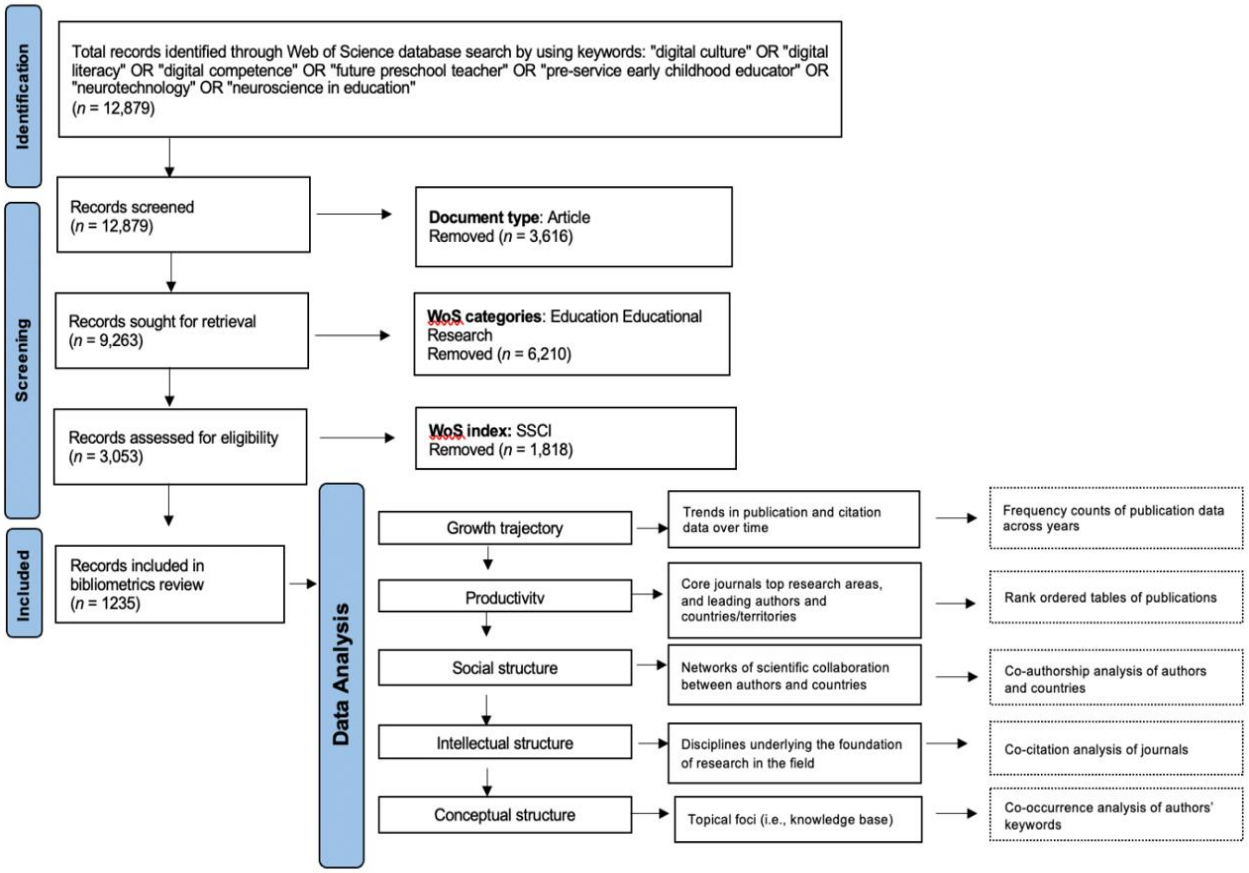

Figure 1. Methodological design

At the initial stage of the research, an extended search query was implemented using key terms: "digital culture" OR "digital literacy" OR "digital competence" OR "future preschool teacher" OR "pre-service early childhood educator" OR "neurotechnology" OR "neuroscience in education".

The result of implementing the search query was the identification of an extensive array of publications (n=12,879), which required subsequent systematisation and refinement of selection criteria for forming an optimal data corpus for bibliometric analysis.

The application of the primary selection criterion by publication type "article" presupposed the inclusion exclusively of journal articles with simultaneous exclusion of monographs, book chapters and conference materials, which led to a reduction in the total number of identified publications to n=9,263.

The subsequent stage of selection was carried out on the basis of applying the Web of Science (WoS) categorical classification with the inclusion of the "Education Educational Research" category, which resulted in the identification of n=3,053 publications. The final selection criterion was based on the publications' belonging to the Social Sciences Citation Index (SSCI) database within the WoS platform, ensuring the formation of a final data corpus for bibliometric analysis in the volume of n=1,235 publications.

From each publication the following were extracted: article title, year of publication, title of periodical, citation indicators, authors' identification data with indication of their institutional affiliation and geographical localisation. Additionally systematised were the authors' research abstracts, keywords and bibliographic lists of cited literature, which ensured the formation of a comprehensive database for conducting bibliometric analysis.

Data analysis procedures

The bibliometric analysis was conducted using VOSviewer software, designed for the visualisation and construction of bibliometric maps. In VOSviewer, analytical units are represented by nodes, the size of which correlates with their significance, spatial positioning reflects the degree of similarity to other nodes, and connections between them are designated by

lines, the thickness of which is proportional to the intensity of interrelationships. The colour coding of nodes indicates their belonging to a cluster. The algorithm for constructing bibliometric maps includes three sequential stages: normalisation of differential characteristics of nodes, two-dimensional projection and clustering [53].

To study the social structure of the scientific sphere, a co-authorship analysis was conducted at the level of individual researchers and countries. The intellectual structure of the discipline was studied using the method of journal co-citation analysis, where groups of frequently cited journals were interpreted as fundamental disciplines of the research area. The conceptual structure was determined through analysis of author keyword co-occurrence, whereby groups of correlating terms represent thematic foci that were addressed in the literature.

Results and Discussion

Evolutionary dynamics of research activity

A bibliometric analysis of publication trends and citation patterns in the field of study

Analysis of bibliometric indicators of research on the formation of digital culture of future preschool organisation teachers based on neurotechnologies (n=1,235) confirms significant scientific influence and maturity of the research subject. The total number of citations amounts to 29,977 with an average indicator of 24.27 per publication, substantially exceeding average values for social sciences and humanities fields. The h-index reaches 83, evidencing the presence of a stable corpus of highly sought-after works. The low level of self-citation (3.4%) with a total number of references of 20,546 emphasises the objectivity of scientific recognition. The data obtained characterise the field as an established scientific direction that has progressed from the formation stage to the phase of conceptual maturity and possesses considerable international authority.

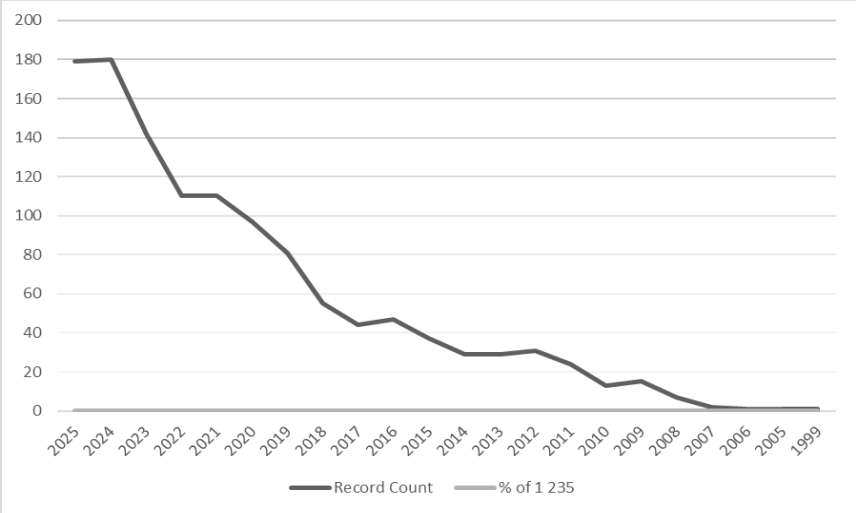

Figure 2. Growth of research on the formation of the digital culture of future preschool teachers based on neurotechnologies

Analysis of the temporal dynamics of publications for the period from 1975 to 2025 **(Figure 2)** demonstrates a qualitative leap in scientific interest in this problematic, starting from the 2010s. The absence of publications in the period from 1975 to 1998 is explained by the insufficient development of the technological base and conceptual apparatus of neurosciences in relation to educational practices. The first isolated works appeared only in 1999, which coincides with the beginning of the active development of digital technologies in education.

Weak publication activity in 2000-2009 (40 works, 3.239% of the total array) is conditioned by the forming character of neuropedagogy as an interdisciplinary field. The subsequent decade (2010-2019) is characterised by a substantial increase to 347 publications (28.097%), which is connected with the development of accessible neurotechnological tools and strengthening interest in scientifically grounded approaches in pedagogy.

The period from 2020 to 2025 is distinguished by the intensification of research activity: the cumulative share of publications constitutes 70.664% of the total corpus (873 works out of 1,235). Such growth is conditioned by several factors: accelerated digitalisation of education in the context of the COVID-19 pandemic, increased accessibility of neurotechnological solutions, and government initiatives for modernisation of pedagogical education.

The maximum indicators of 2024-2025 (180 and 179 publications respectively) testify to the stabilisation of publication activity at a high level and the achievement of a certain maturity of the research direction under study.

Productivity

Core journals top research areas, and leading authors and countries/territories, among others

Table 1. WOS Data Analysis

Criteria	Data	Records	% of 1235
Web of Science Index	Social Sciences Citation Index (SSCI)	1235	100.000
	Science Citation Index Expanded (SCI-EXPANDED)	117	9.474
	Arts & Humanities Citation Index (A&HCI)	99	8.016
	Conference Proceedings Citation Index – Social Science & Humanities (CPCI-SSH)	1	0.081
Web of Science Categories	Education Educational Research	1235	100.000
	Linguistics	112	9.069
	Language Linguistics	83	6.721
	Computer Science Interdisciplinary Applications	67	5.425
Research Areas	Education Educational Research	1235	100.000
	Linguistics	112	9.069
	Computer Science	67	5.425
	Communication	65	5.263
Authors	Guillén-gámez FD	10	0.810
	Mcgarr O	9	0.729
	Kohnke L	8	0.648
	Palacios-rodríguez A	8	0.648
Publication Titles	Education and Information Technologies	171	13.846
	Comunicar	65	5.263
	Computers Education	61	4.939
	Interactive Learning Environments	35	2.834
Countries/Regions	Spain	222	17.976
	USA	211	17.085
	Peoples R China	151	12.227
	Australia	96	7.773
Document Types	Article	1235	100.000
	Early Access	110	8.907
	Proceeding Paper	1	0.081
	Retracted Publication	2	0.162
Languages	English	1161	94.008
	Spanish	68	5.506
	German	3	0.243
	Portuguese	2	0.162

Analysis of research productivity **(Table 1)** based on a sample of 1,235 publications demonstrates that the analysed publications (100%) are indexed in the Social Sciences Citation Index (SSCI), which is explained by the application of the corresponding search filter. At the same time, part of the works are additionally represented in the Science Citation Index Expanded (9.474%) and Arts & Humanities Citation Index (8.016%), indicating the interdisciplinary character of research that goes beyond the boundaries of traditional social sciences and touches upon natural science and humanities areas of knowledge.

The thematic classification of selected works relates to the category of educational research (100%). However, a substantial part of publications is also classified in related areas: linguistics (9.069%), language studies (6.721%) and interdisciplinary applications of computer sciences (5.425%). This distribution emphasises the significance of linguistic and technological aspects in the process of forming teachers' digital culture.

Analysis of research areas similarly confirms the interdisciplinary character of the problematic under study. Besides basic educational research, a significant place is occupied by linguistics (9.069%), computer sciences (5.425%) and communication (5.263%), reflecting the complexity of tasks connected with the implementation of neurotechnologies in pedagogical education.

The distribution of publication activity amongst authors is characterised by the absence of clear dominance of individual researchers. The most productive authors – Guillén-Gámez FD (0.810%), McGarr O (0.729%), Kohnke L and Palacios-Rodríguez A (0.648% each) – demonstrate a broad scientific community with distributed research activity.

Analysis of leading journals by number of publications reveals the main publications in the field of educational technologies. The journal "Education and Information Technologies" occupies first place (13.846%), followed by "Comunicar" (5.263%) and "Computers & Education" (4.939%). The distribution demonstrates a focus of research on technological innovations in education and issues of intercultural communication.

The geographical distribution of publications demonstrates a concentration of research activity in three main regions [54-57]. Spain leads with an indicator of 17.976%, followed by the USA (17.085%) and China (12.227%). Australia represents the fourth most significant research centre (7.773%), reflecting various national strategies and priorities in the field of digitalisation of preschool education.

All publications in the sample are presented in the format of scientific articles (100%), which is conditioned by the application of the corresponding selection filter. A significant proportion of works (8.907%) are in early access status, indicating the high topicality of the research direction and intensity of the publication process.

The language distribution of publications shows the predominance of English (94.008%) as the main medium of international scientific communication. The presence of Spanish (5.506%) corresponds to the high research activity of Spanish-speaking countries and reflects the regional peculiarities of the development of scientific direction.

Social structure

Networks of scientific collaboration between authors and countries

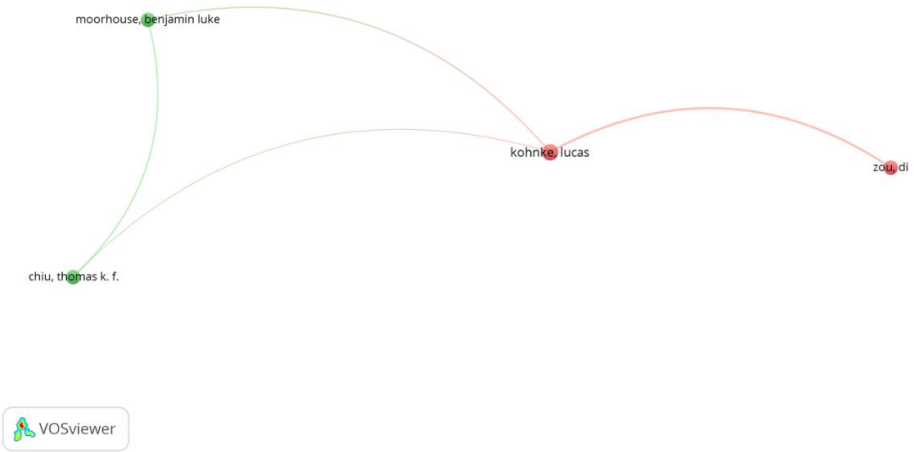

Figure 3. Networks of scientific collaboration between authors (n=4)

Cluster analysis of scientific collaboration **(Figure 3)** revealed the formation of two main research groups amongst leading authors (*n*=4) with their own directions of scientific inquiry and methodological approaches in the field under study. The red cluster (*n*=2) unites researchers Kohnke, Lucas and Zou, Di. The visualisation demonstrates the presence of stable collaborative connections between the authors, indicating joint research activity and coordinated scientific efforts within the framework of the thematic under study. The green cluster (*n*=2) includes Chiu, Thomas K. F. and Moorhouse, Benjamin Luke.

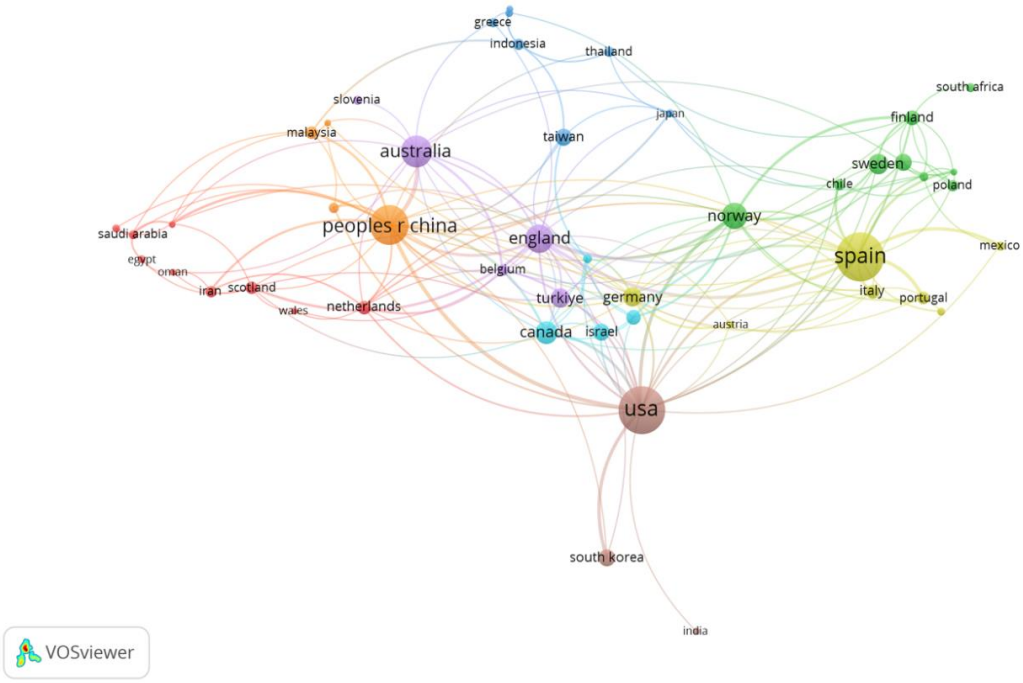

Figure 4. Networks of scientific collaboration between countries (n=48)

Network analysis of international collaboration (*n*=48) revealed eight research collaboration clusters **(Figure 4)**, reflecting the complex architecture of global research connections in the field of neurotechnology integration into teacher education. The collaboration structure demonstrates the influence of geopolitical, economic, cultural-linguistic, and technological factors on the formation of international research alliances.

The green cluster (*n*=9), coordinated by Spain, demonstrates unique transnational collaboration bringing together Brazil, Chile, Ecuador, Finland, Norway, Poland, South Africa, Sweden, and Turkey. Spain's central role is determined by participation in Erasmus+ programs, historical and linguistic ties with Latin American countries, and investments in educational technologies. The presence of Scandinavian countries reflects their status as leaders in educational innovation, willing to share experience with developing economies.

The brown cluster (*n*=3)-the USA, India, and South Korea-represents a strategic alliance of technological leaders. The USA dominates in neuroscience and educational technologies, India contributes competencies in the IT sector and artificial intelligence, and South Korea provides advanced solutions in digital education.

The orange cluster (*n*=4), led by China, includes Malaysia, Singapore, and the UAE, reflecting regional integration within Asian economic initiatives. China's leadership is determined by government investments and the Belt and Road Initiative strategy. Singapore serves as a regional innovation hub, while the UAE provides connections to the Middle Eastern region.

The purple cluster (*n*=5), led by Australia, includes Belgium, England, Slovenia, and Turkey. Australia serves as a connecting link between European research traditions and Asian educational innovations, facilitating technology transfer between regions.

The light blue cluster (*n*=7) brings together Japan, Cyprus, Greece, Hungary, Indonesia, Taiwan, and Thailand within Asian-European collaboration. Japan provides the technological foundation, European countries contribute methodological expertise, and developing Asian economies offer markets for testing innovations.

The yellow cluster (*n*=7) represents a classic European coalition: Austria, Denmark, Germany, Italy, Portugal, Spain, and Mexico. The alliance is determined by EU institutional frameworks and joint research programs. Mexico's inclusion is explained by cultural-linguistic ties with Spain and Portugal.

The red cluster (*n*=9) unites predominantly developing countries: Egypt, Iran, Kazakhstan, the Netherlands, Oman, Pakistan, Saudi Arabia, Scotland, and Wales. The Netherlands acts as a technology donor, providing advanced solutions, while other participants provide conditions for adapting innovative approaches.

The cyan cluster (*n*=4)-Canada, Ireland, Israel, and New Zealand-represents an English-speaking research network based on common educational traditions, linguistic proximity, and high technological level.

The architecture of international collaboration demonstrates the absence of rigid geographical binding, indicating the global nature of research. Cluster formation is determined by the interaction of technological capabilities, economic interests, cultural-linguistic connections, and institutional frameworks. The central position of the USA, China, Spain, and Australia reflects their role as coordinating centers of global research initiatives in the field of digital culture formation among educators based on neurotechnologies.

Intellectual structure

Disciplines underlying the foundation of research in the field

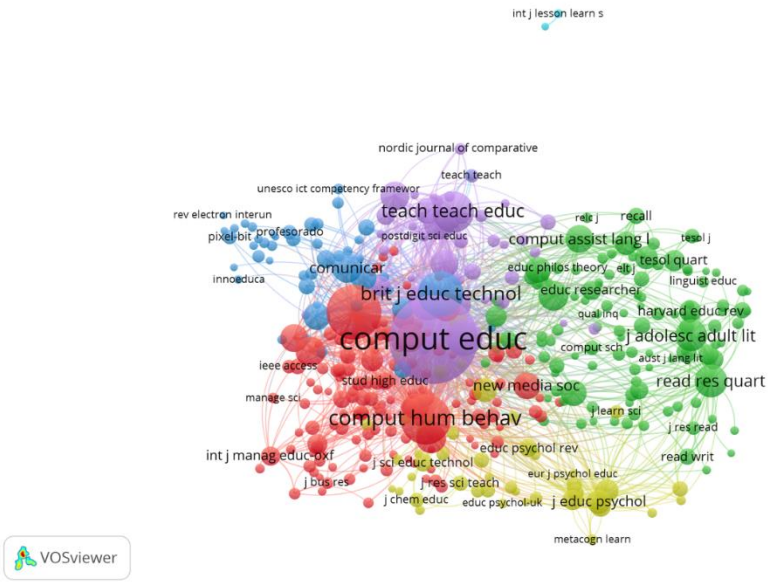

Figure 5. Co-citation analysis of journals (*n*=398)

Co-citation analysis of 398 journals revealed **(Figure 5)** an interdisciplinary research landscape organized into six clusters, reflecting the multifaceted nature of digital culture formation among future preschool educators through neurotechnology integration.

The red cluster (n=140) is the largest grouping, uniting behavioral sciences, human-computer interaction, and computer education. The predominance of "Computers in Human Behavior" and "Computers & Education" indicates a focus on understanding the impact of digital technologies on pedagogical practices and learning outcomes.

The purple cluster (n=119) concentrates on applied linguistics, educational technologies, and developmental psychology. Journals "Computers and Composition", "Child Development", and "Applied Linguistics" connect computer-assisted language learning with developmental psychology, emphasizing cognitive and linguistic aspects of digital competence formation.

The blue cluster (n=48) addresses educational technology implementation and digital competence models. Journals "British Journal of Educational Technology", "EDMETIC", and "European Journal of Education" reflect institutional perspectives on technology integration and attention to DigComp frameworks.

The yellow cluster (n=45) focuses on educational psychology and cognitive learning. "Educational Psychology Review" and "Contemporary Educational Psychology" provide theoretical foundations for understanding how neurotechnologies can enhance cognitive development in preschool education.

The green cluster (n=43) centers on teacher education and innovations. Journals "Asia-Pacific Journal of Teacher Education" and "Journal of Education Policy" emphasize pedagogical competencies necessary for effective neurotechnology integration.

The light blue cluster (n=3) is represented by publications "China Educational Technology" and "Professional Development in Education", highlighting research on lesson planning in Asian educational systems.

Network visualization demonstrates dense connections between red, purple, and green clusters, reflecting convergence of computer education, linguistic development, and teacher training. Educational psychology (yellow cluster) serves as a connecting element, providing theoretical foundations for practical technology implementation.

The journal landscape indicates that digital culture formation among future preschool educators requires integration of behavioral sciences, developmental psychology, linguistic development, and pedagogical innovations. Neurotechnology application must be grounded in theoretical foundations while simultaneously addressing practical implementation challenges and teachers' professional development.

Conceptual structure

Topical foci (i.e., knowledge base)

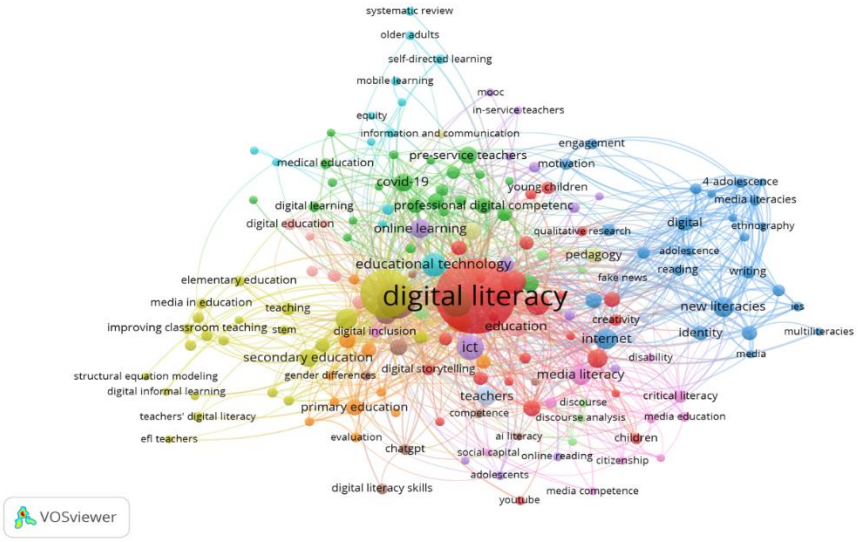

Figure 6. Co-occurrence analysis of authors' keywords (*n*=179)

Analysis of keywords **(Figure 6)** with the central position of the term "digital literacy" demonstrates thirteen thematic clusters, reflecting the structure of research in the field of forming the digital culture of future preschool education teachers based on neurotechnologies.

The blue cluster (*n*=26) forms the conceptual core, uniting fundamental concepts of digital literacy, digital citizenship and digital technologies. The presence of categories children, pre-service teachers, creativity, critical thinking testifies to a focus on developing complex competences of future educators capable of integrating neurotechnologies into work with preschool children. The green cluster (n=25) concentrates on digital competences in professional pedagogical education. The dominance of terms digital competencies, teacher digital competence is directly connected with the task of forming in future teachers a system of competences for working with neurotechnologies. The term Covid-19 demonstrates the influence of the pandemic on the accelerated implementation of digital technologies. The inclusion of concepts digcompedu, machine learning testifies to the need for interdisciplinary training of educators who understand the neurobiological foundations of learning.

The yellow cluster (n=22) focuses on formal education and defines the institutional context of applying neurotechnologies in the system of continuous education. The concepts 21st century abilities, STEM, structural equation modeling reflect contemporary requirements for training educators capable of applying research methods to evaluate the effectiveness of neurotechnological tools. The pink cluster (n=14) centres on technological toolkit, including online learning, MOOC, ICT, directly connected with forming the digital culture of future teachers. The remaining clusters encompass educational equity and language learning (n=13), computational thinking and programming (n=12), artificial intelligence and digital inequality (n=11), media education and social inclusion (n=11).

The conducted analysis revealed substantial discrepancies between the stated topic and the structure of the research field. The specificity of preschool education proves to be marginalised: terms directly connected with preschool age (preschool, kindergarten) are represented minimally and do not occupy central positions in the semantic network. The dominance of themes related to adolescent and youth audiences substantially limits the applicability of the revealed results to the context of preschool pedagogical education.

Most problematic appears the practically complete absence of neurotechnological themes in the analysed array. The term "neurotechnologies" in its strict scientific understanding (neurointerfaces, neurobiofeedback systems, neuroimaging, neurostimulation) has not been identified in the cluster structure. The discovered theme "Artificial Intelligence in Education" represents a fundamentally different technological area based on algorithmic modelling rather than on direct interaction with neurophysiological processes. The identification of artificial intelligence with neurotechnologies represents a conceptual error.

The revealed discrepancy testifies that the research field of forming the digital culture of preschool education teachers based on neurotechnologies is at an initial stage of development and does not possess a sufficient publication base for forming a separate thematic cluster in international scientific literature. Thus, the correlation of the revealed themes with the stated problematic demonstrates simultaneously both potential for conceptual substantiation through using developments in the field of teachers' digital competence and substantial limitations connected with insufficient representation of the specificity of preschool education and practically complete absence of neurotechnological problematic.

Conclusion

The rapid development of neurotechnologies and their penetration into the educational sphere actualise the necessity of rethinking approaches to professional training of preschool

education teachers. The possibility of using EEG, fNIRS, eye-tracking and neurofeedback for objective assessment of neurocognitive peculiarities of preschool children's development requires the formation in future teachers of new competences that go beyond the boundaries of traditional digital literacy.

The conducted bibliometric study of the scientific landscape of forming the digital culture of future preschool education teachers based on neurotechnologies has allowed for obtaining an understanding of the state and prospects of development of this area of knowledge. Analysis of 12,879 publications from the Web of Science database over a fifty years period (1975-2025) revealed growth in scientific interest in the research subject in the period 2020-2025, testifying to the formation of a new direction at the intersection of early childhood pedagogy, neuroscience and digital technologies. This tendency reflects the global demand for educational systems for scientifically grounded approaches to personalisation of preschool education. The revealed geographical concentration of research in Spain, the USA and China indicates uneven development of the direction on a global scale. The interdisciplinary character of publications, encompassing education, linguistics, computer sciences, medicine, and psychology, confirms the complexity of the task of integrating neurotechnologies into pedagogical practice and the necessity of a comprehensive approach to training specialists. The existence of two weakly interacting research groups testifies to the necessity of creating platforms for interdisciplinary dialogue and the consolidation of scholars' efforts. The research field being at an initial stage of development simultaneously represents both a challenge and an opportunity for forming theoretical and methodological foundations for training teachers of a new type.

The results obtained have strategic significance, creating a scientifically grounded base for designing educational programmes that include mastery of neurotechnologies (EEG, fNIRS, eye-tracking, neurofeedback) as tools of professional activity of a preschool organisation teacher. Practical realisation of the data obtained will make it possible to overcome the gap between the rapid development of neurotechnologies and their application in educational practice, ensuring the training of specialists capable of making grounded pedagogical decisions based on objective data about a child's development. Prospects for further research are connected with developing specific models for integrating neurotechnologies into educational programmes for training preschool education teachers, studying the effectiveness of various formats of teaching future specialists to work with neurotechnological equipment, as well as creating a national research network capable of contributing to the development of global scientific discourse in this promising field.

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