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Transformation of the spiritual values of future primary school teachers in the context of globalisation

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Abstract. The purpose of the study was to identify the features of transforming the spiritual values of primary school teachers under the influence of contemporary socio-cultural challenges. By combining a multifaceted systematic analysis of academic sources with an empirical survey of 50 students at various levels of study at the E.A. Buketov University of Karaganda, a comprehensive picture of the axiological dynamics of young people was formed, which was analysed using Student's t-test and the Mann-Whitney test. The analysis of the data obtained demonstrated the stability of the value core, in which the dominant positions retained the categories of physical and psychological health, whose indicators increased from 4.75 to 4.81 points, and a happy family life, which increased from 4.74 to 4.79 points. In parallel with this, an increase in the pragmatic vector among graduates was recorded, which was manifested in a statistically significant increase in the importance of material security from 4.57 to 4.64 points and organisational abilities from 4.21 to 4.35 points. Special attention was drawn to the consistently low significance of the value of "power", which received a minimum of 2.61-2.66 points, confirming the instability of the humanistic orientation of the pedagogical profession before the influence of Western models of social domination. Simultaneously, there was a slight decrease in the priority of education as an abstract goal from 3.95 to 3.87 points among 5th-year students, which was explained by their successful adaptation to professional status and transition to the practical implementation of professional knowledge. The recorded changes in hierarchy reflected the establishment of a complex balance between traditional ideals and the need to adapt to the requirements of a globalised labour market. The general conclusions confirmed that a conscious attitude to spiritual values is an integral component of the teacher's professional competence, capable of ensuring the harmonious development of the student's personality. The practical significance of the study consisted in the substantiation of the need to integrate elements of spiritual education into the educational process for improving the personal self-realisation of future specialists

Keywords: student; higher educational institution; educational process; ethical education

INTRODUCTION

In the context of globalisation, there is an urgent need to preserve national cultural traditions and moral guidelines in teacher education. The dynamic changes in educational standards and social expectations observed since 2019 require future primary school teachers to adapt to new conditions without losing their cultural identity. The problem lies in the need to foster teachers who are spiritually developed, capable of withstanding a crisis of values and bringing up a harmonious younger generation. Investigation of the transformation of student values is critical to stabilising the national education system

Contemporary scientific discourse considers the transformation of a teacher's professional profile as a complex

response to the challenges of a globalised world, where personal guidelines become the foundation of professional skills. In particular, B. Paridinova *et al.* (2023) investigated the factors of developing the spiritual worldview of future teachers, focusing on the fact that the educational environment of a higher education institution should become a defining space for laying moral standards. Researchers claim that it is reflection that determines the prerequisites and effects of creating a spiritual worldview, allowing the teacher to effectively face the challenges of contemporary education.

The problem of adapting educational content to new requirements was covered in the study by A. Mukhanbetzhanova *et al.* (2024), who emphasised the need to

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develop specialised courses that promote the fostering of basic professional competencies through the integration of spiritual values into the educational process. The researchers viewed higher education as the outcome of a master's degree programme, in which the curriculum should reflect not only technical requirements but also the prospects for the development of culture and the arts. In turn, M.Y. Al-imjonova (2021) emphasised the critical role of national values in the training of primary school teachers, noting that the development of interpersonal skills and leadership qualities is an integral part of a teacher's personal development. The researcher pointed out that participation in clubs, excursions and social events creates an environment in which students can intensively improve their social competencies and interpersonal communication skills.

A separate layer of research was devoted to the search for "missing dimensions" in professional development programmes for teachers. S.K. Wagle *et al.* (2023) substantiated the need for internal transformation of teachers through an appeal to the categories of spirituality and consciousness. This approach encourages teachers to recognise their role as co-creators of peace, emphasising that "inner awakening" is a key element of professional fulfilment in a global crisis. The relationship between the value attitudes of management and the effectiveness of the educational system was highlighted by A. Nurabadi *et al.* (2021). Their research has shown that spiritual leadership directly affects the performance of primary school teachers and students' academic performance. The paper proved that the combination of instructional, transformational, and spiritual leadership creates conditions for maximum self-realisation of the teacher, which has a positive effect on the success of students. In addition, S. Canli & H. Demirtas (2018) revealed the concept of a "global teacher" who is forced to balance between the demands of technological progress and the humanistic mission of education. They proved that while globalisation makes it easier to access information, technological dominance can negatively affect thinking, putting technology above humanistic benchmarks. Thus, the analysis confirmed that the transformation of values is a systematic process that requires rethinking the entire training strategy for future teachers.

The purpose of the study was to establish the nature and dynamics of structural changes in the system of spiritual guidelines for future primary school teachers under the influence of globalisation challenges. The objectives of the study were: to determine the actual hierarchy of students' life values and trace their transformation throughout the entire period of study in a higher education institution; to analyse the degree of influence of factors of globalisation, digital technologies and Western culture on the ratio of personal and professional priorities of future teachers; to substantiate and test in practice the effectiveness of methods involving small-group interaction, reflective analysis, and problem-based discussions in the process of fostering students' spiritual maturity.

MATERIALS AND METHODS

The research methodology was based on the integration of a multi-faceted system analysis of scientific sources and experimental verification of the transformation of spiritual values of future teachers. The theoretical stage provided for the analysis of psychological and pedagogical literature at the general, partial, and specific levels to determine the impact of globalisation processes on education. In the process of substantiation, the principles of historicism, consistency, and objectivity were applied, which allowed considering spiritual guidelines as a dynamic system that changes under the pressure of socio-cultural transformations and the dominance of pragmatic models. The theoretical foundation of the study covered the analysis of concepts by O.F. Cantekin (2015) on the risks of dehumanisation of education, and the papers by A. Nurabadi *et al.* (2021) and B. Paridinova *et al.* (2023) on the factors of forming a worldview and spiritual leadership in the pedagogical environment.

The empirical part of the study was carried out in 2025 at the E.A. Buketov University of Karaganda. A random sample of 50 respondents was divided into two groups: first-year students ($n = 25$, aged 17-19), representing the initial stage of their studies, and fifth-year students ($n = 25$, aged 21-23), representing the final stage of their professional training. This approach allowed tracing the evolution of value orientations during the period of stay in a higher education institution.

The main data collection tool was an anonymous written questionnaire, which was conducted in two specially equipped university classrooms under the direct supervision of teachers to ensure a high level of reliability of the results obtained. Respondents were offered a form with a list of 20 life values, which were initially arranged in alphabetical order to avoid subjective influence on the choice of priorities. The list included such categories as physical and psychological health, happy family life, love, material well-being, interesting job, professionalism, spirituality (kindness, compassion), freedom, faith in God, and work for the benefit of others. The task of students was to distribute these values according to the level of their significance as life guidelines using a five-point scale, where 5 points indicated the highest importance, and 1 point – the lowest.

The process of forming values during professional training was also based on a set of pedagogical methods described by B. Zhekiyayeva *et al.* (2020) and N. Yunusaliyeva (2022), in particular, explanatory and illustrative, reproductive, problem-based, and partially research-based. Emphasis was placed on the use of small-group interaction, reflexive tasks, ethical discussions, and scientific conferences, which contributed to the activation of the internal potential of future teachers. Statistical processing and interpretation of the results were performed using SPSS software suite. Descriptive methods (calculation of arithmetic mean and standard deviation), and methods for testing statistical hypotheses were used for the analysis. To compare the average values between groups of 1st-year students and graduates, the Student's t-test was used (under normal

distribution conditions), and in cases of deviation from the norm, the Mann-Whitney criterion was used. Visualisation of the obtained data was implemented through the construction of comparative tables and histograms, which allowed illustrating shifts in the value hierarchy of students under the influence of globalisation

RESULTS AND DISCUSSION

Theoretical analysis of the transformation of spiritual values in scientific discourse

At the general theoretical level, it was established that the spiritual development of future teachers requires a deep philosophical and pedagogical rethinking, since the teacher should act not only as a translator of knowledge, but also as a conductor of spiritual development of students. According to the conclusions of M.A. Yepikhina (2022), the revival of the culture and spirituality of the state is possible only through the training of educated professionals who rely on strong moral and ethical guidelines.

During theoretical analysis, the absence of a single definition of the concept of "spirituality" in contemporary science at the time of 2024 was revealed. In particular, M. Bekbayeva *et al.* (2022) considered spirituality through the prism of religiosity and conscious management of personal activities in accordance with reference models of human existence. In turn, S.-L. Cheng & K. Xie (2018) and M. Mahipalan & S. Sheena (2018) emphasised that in the pedagogical context, spirituality is an intellectual and emotional sphere aimed at filling life with meaning. M. Paul *et al.* (2020) and O.V. Mekhed (2024) complemented these views by arguing that spirituality is a unique quality that reveals the moral meaning of a teacher's actions and makes their activities an organic part of the educational process.

The analysis focused on the institutional crisis of education. O.F. Cantekin (2015), O.T. Mamajonov (2024) and O. Pobirchenko & V. Honcharuk (2024) argued that traditional university systems often function as closed distributors of knowledge, which creates a contradiction between the needs of the individual for spiritual development and the pragmatic factors of the educational process. This requires a revision of educational goals and a return of the category of "spirituality" to the practical plane of higher education. A. Mukhanbetzhanova *et al.* (2024) substantiated the need to restructure educational content and develop specialised courses that would integrate spiritual components into the structure of professional competencies of master's degree students.

Analysis of concepts of M.Y. Alimjonova (2021) and M. Roganova *et al.* (2023) showed that improving interpersonal and social skills is an integral component of primary school teacher training. In particular, this includes teamwork skills, the use of ICTs in a professional environment, and the development of leadership competencies. O.B. Botalova *et al.* (2016) and I.A.W. Chrismastianto *et al.* (2022) defined values as the basis for the orientation of the educational process, where spiritual education is considered primarily as a process of forming moral standards and ideals.

An important result of the theoretical stage was the investigation of the impact of globalisation on individual value systems. O. Ilina & Ye. Huba (2021) noted that the current state of public life puts forward special requirements for the development of graduate orientations, where each value plays the role of a resource for further personal development. Ye. Bidenko (2020) emphasised that the mechanism for determining values is closely related to the political and cultural structure of the country. As noted by N. Aboobaker *et al.* (2019) and A. Kalimova *et al.* (2022), students as the future intellectual elite should be prepared for life through introduction to the spiritual heritage of humanity, which is a necessary condition for the stability of the state.

The study of innovative approaches has shown that the humanisation of education depends on the harmonious development of personal qualities of the teacher, which guarantees justice and tolerance in the educational process (Teo & Huang, 2019; Wang & Hall, 2019). V. Tsina *et al.* (2020) emphasised the importance of the cultural component, which contributes to the development of a holistic view of the world and respect for cultural diversity through cross-cultural exchange in the university environment. The final aspect of the theoretical analysis was the allocation of tools for value fostering. Based on B.A. Zhekibayeva *et al.* (2020), methods of influencing the spiritual sphere were systematised:

- explanatory and illustrative (organisation of information perception);
- reproductive (application of knowledge based on a sample);
- problem-based search (solving of ethical problems);
- partial research method (intellectual games).

These methods, supplemented by strategies of N. Yunusalieva (2022) on small-group interaction and reflexive analysis, became the foundation for further empirical testing of student value transformation. A systematic analysis of the professional training of future primary school teachers determined its transformation in the context of large-scale social changes. This is conditioned by historical changes in the educational paradigm, where the development of spiritual values of young people becomes not just an educational task, but a priority area for stabilising the national education system. It was established that the contemporary model of training should be based on the search for new ways to implement moral education, considering the challenges of globalisation and digitalisation. This conceptual approach contributed to the substantiation of the self-directed process of professional development, which orients students to search for value life orientations and contributes to the development of personality as an active creative subject of educational activity. As part of this process, the teacher becomes a guide who encourages the disclosure of the inner potential and self-expression of the future teacher. Thus, the theoretical rethinking of the training system confirms that spirituality is an intellectual and emotional

sphere that fills the professional activity of a teacher with humanistic content.

Analysis of empirical data on student value transformation

The diagnostic tool provided for the assessment of 20 basic life values covering the spiritual, professional, material and social spheres of life. The use of a five-point scale

helped to mathematically determine the degree of significance of each indicator and identify statistically significant differences between groups. The results obtained demonstrate a dynamic picture of the transition from idealised representations to more pragmatic models of behaviour dictated by contemporary socio-economic conditions. The generalised hierarchy of values, derived from the survey results, is presented in Table 1.

Table 1. Hierarchy of life values of future primary school teachers

Life values		Points	
		1 st -year	5 th -year
1	Physical and psychological health, absence of diseases	4.75	4.81
2	Happy family life	4.74	4.79
3	Love	4.67	4.66
4	Having loyal friends	4.65	4.67
5	Material security and well-being	4.57	4.64
6	Interesting job, the possibility of self-expression in the work	4.43	4.45
7	High professionalism	4.37	4.42
8	Organisational skills, enterprise, efficiency, ability to achieve goals	4.21	4.35
9	Spirituality, kindness, compassion	4.19	4.28
10	Education, improvement of the cultural and intellectual level	3.95	3.87
11	Freedom and independence in actions and thoughts	3.86	3.84
12	Life wisdom and maturity of thoughts	3.75	3.81
13	Theatre, literature, music, tourism, physical activity, etc.	3.71	3.62
14	Spiritual comfort, stable and peaceful life without changes	3.38	3.45
15	Active life position	3.24	3.41
16	Public recognition, authority	2.94	3.25
17	Work for the benefit of other people	2.83	2.79
18	Recognition of truth, spiritual search	2.76	2.78
19	Faith in God	2.72	2.69
20	Power, ability to influence other people	2.61	2.66

Source: compiled by the authors

Most of the values were recognised as significant for 1st-year students, but there was some transformation of

values depending on the course of study of students. Based on these tables, a histogram was performed (Fig. 1).

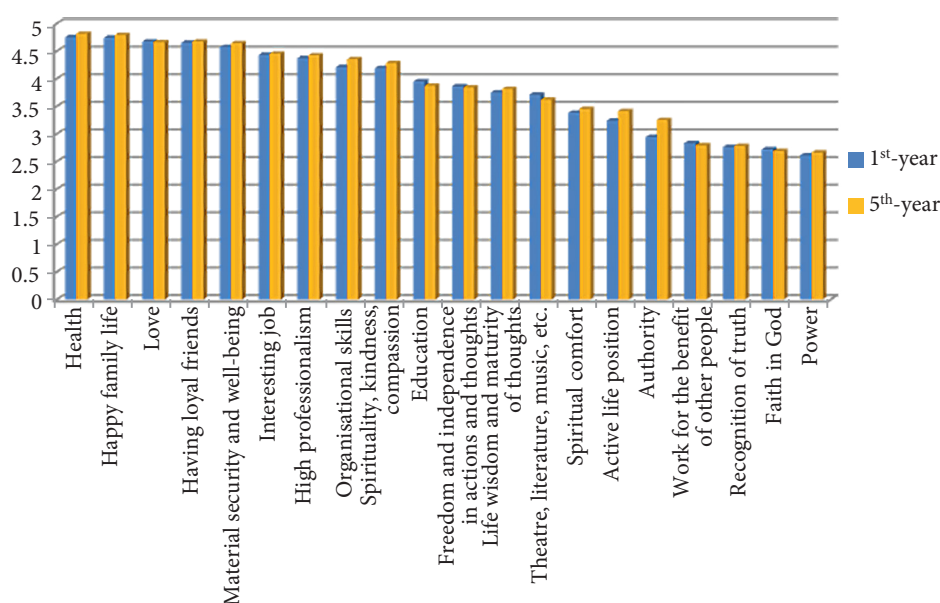


Figure 1. Changing the hierarchy of student values depending on their year of study

Source: compiled by the authors

The results of the survey allowed building a hierarchy of life priorities of future teachers (Table 1) and tracing their transformation in the course of learning (Fig. 1). The analysis confirmed that the core of the value system of both groups of respondents remains stable: the highest scores received personal life values – physical and psychological health (4.75-4.81), happy family life (4.74-4.79), and love (4.66-4.67). The growing importance of health and family among 5th-year graduates indicates the development of a more mature view of life and awareness of the importance of social support before entering an independent professional environment.

However, the process of professional training makes significant adjustments to other levels of hierarchy. In particular, graduates have an increase in the pragmatic vector: points on such positions as “material security” (from 4.57 to 4.64) and “organisational skills and entrepreneurship” (from 4.21 to 4.35) significantly increase. This indicates that under the influence of globalisation and digital technologies, senior students are beginning to perceive financial independence and leadership qualities as necessary tools for successful adaptation to the contemporary labour market.

An interesting fact is that the importance of education as a value among graduates has slightly decreased (from 3.95 to 3.87). This is explained by psychological adaptation: if in the 1st-year education is perceived as an abstract goal, then in the 5th-year students already consider it as a tool that they have significantly mastered. A similar decrease in interest in theatre, literature, and tourism (from 3.71 to 3.62) may indicate a temporary narrowing of the circle of interests due to the full concentration of graduates on the issues of future employment and professional integration.

Separately, it is necessary to highlight the block of values that were found on the periphery of the consciousness of future teachers. Spiritual search, faith in God, and public recognition received the lowest scores (in the range of 2.69-3.25 points). Especially significant is the last place of value of “power” (2.61-2.66). Despite the powerful influence of Western culture, where career success is often associated with dominance and status, Kazakh student teachers demonstrate resilience to this trend. This confirms the thesis that the teacher’s professional consciousness continues to be dominated by a humanistic and altruistic orientation, in which working with children is perceived as service, and not as a path to power. Thus, the recorded transformation of values reflects a complex balance: on the one hand, students remain true to the traditional ideals of family and health, and on the other, they are forced to become more pragmatic to respond to the challenges of a globalised economy.

The paper analysed the evolution of students’ value priorities in various courses of the educational process, and the impact of globalisation processes on changing their life values. Ya.A. Nurumbekova & Z.U. Xudoykulova (2022) in their research concluded that the values of students are transformed as they study and socialise at the university. They noted that students are gradually rethinking

their life principles, focusing on the future profession and the requirements of society. This study, like that of the authors in question, noted a gradual increase in the importance of values relating to personal well-being and professional achievements. In contrast to other researchers, who focused on the gradual depth of theoretical values in the educational process, this study has shown that the importance of values such as health, happy family life and love remains stable, but simultaneously new values appear, such as financial stability.

M. Zhilgildinova *et al.* (2022) presented data in their research showing significant differences in the values of 1st-year and graduate students, depending on their involvement in the educational process and professional activities. They noted that graduates prioritise practical values, such as material well-being and career growth, which was also confirmed in this study, where values related to material security and professionalism were more highly appreciated by senior students. The study confirmed the hypothesis that graduates have significantly changing priorities in the assessment of values, and there is an increase in the importance of career orientations and professional achievements.

The development of spiritual values requires a systematic, personal, activity, competence, axiological, cultural, synergistic, acmeological, resource, innovation, and research conceptual approach that can optimise this process, make it more effective and responsive to the needs of society. The paper considered a systematic approach in the process of preparing future primary school teachers to perform an educational function in the process of fostering spiritual values. It suggested considering this process as a dynamic system that is part of the training structure of future primary school teachers. Analysis of the paper by S. Yadi *et al.* (2024) allowed comprehensively considering the problem of transformation of pedagogical professionalism in contemporary conditions through the prism of systemic and empirical approaches. According to the conclusions, the use of a systematic approach contributed to the development of a holistic training model that determined the relationship between its components and key conditions for the functioning of the educational system in a changing globalisation environment. Empirical data by S. Yadi *et al.* (2024) demonstrated a deep differentiation of students’ values depending on the stage of their training: active involvement in professional activities encourages graduates to give preference to practical orientations, in particular material well-being and career growth. This fully confirmed the hypothesis of this study about a significant change in priorities and strengthening the pragmatic vector among senior students.

In this paper, it was found that the value of “power” consistently occupies the last position in the hierarchy of future teachers (2.61-2.66 points), which indicates stability to Western models of success, where career growth is often associated with dominance and social status. M. Bekbayeva *et al.* (2022) pointed out that the student value system is not static and undergoes significant transformations in

the process of university socialisation. Although the conducted research confirmed the thesis about the dynamics of values (in particular, pragmatism is growing in the 5th-year), the low importance of power remains an unchanged characteristic, which is explained not only by the specifics of pedagogical activities focused on the development of the individual, but also by a general cultural feature, according to which “power” is not associated with the humanistic mission of education. Consequently, there is a tendency for the predominance of humanistic values focused on improving life conditions, social assistance, and professional development. Furthermore, there is a decrease in the importance of spiritual and socially oriented values. Perhaps this is conditioned by the need to integrate with the current socio-economic conditions and changes in the structure of professional identity of future teachers against the background of globalisation processes.

CONCLUSIONS

The generalisation of the results of the study allowed stating the complex dynamics of the transformation of value orientations of future primary school teachers under the influence of globalisation calls. A systematic analysis of empirical data confirmed the relative stability of the axiological core of the individual, where the leading positions invariably occupy the categories of physical and psychological health (increase from 4.75 to 4.81 points), happy family life (from 4.74 to 4.79 points) and love (stable 4.66-4.67 points). However, there was a clear tendency to strengthen the pragmatic vector among graduates in comparison with 1st-year students. A significant increase in the importance of material security (from 4.57 to 4.64 points), high professionalism (from 4.37 to 4.42 points) and organisational skills (from 4.21 to 4.35 points) indicates the intensive adaptation of young people to socio-cultural conditions and requirements of information civilisation.

It was proved that the process of professional training is accompanied by a rethinking of instrumental values. The

decrease in the priority of education (from 3.95 to 3.87 points) and interest in cultural leisure, including theatre and literature (from 3.71 to 3.62 points), was explained by the psychological adaptation to professional status and maximum concentration on the issues of future employment. A consistently low position of value of “power” was recorded, which received a minimum of 2.61-2.66 points, which indicates the preservation of the humanistic orientation of the teacher’s professional consciousness and their orientation to service, and not to power control. The identified transformations reflect the development of a dynamic balance between traditional moral ideals and new demands for social success, where spiritual maturity becomes a necessary component of professional competence. The integration of spiritual values into pedagogical activity contributes to the harmonious development of the specialist’s personality, preventing dehumanisation of the educational space.

Prospects for further scientific research consist in a detailed study of the specifics of preparing future teachers for the implementation of spiritual and ethical education in the systems of extracurricular and complementary education. The priority area is the scientific substantiation and testing of innovative models of spiritual culture development in the educational process of higher education as a strategic element for managing the quality of education. The study of the direct dependence between the level of spiritual maturity of a teacher and the intensity of moral development of the personality of primary school students in the context of a changing globalisation environment remains relevant.

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Integration of environmental and inclusive education in the professional training of primary school teachers

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Abstract. The aim of the study was to identify the specific features, challenges and prospects for developing environmental competence in future primary school teachers at the Arabaev Kyrgyz State University. The research methodology was based on a mixed-methods approach and included a formative experiment conducted at the university with the participation of 50 students (experimental and control groups), as well as a comparative analysis of questionnaire results before and after the implementation of a 36-hour specialised programme. The study identified the level of students' environmental knowledge and skills, as well as the most effective pedagogical approaches and models contributing to the development of their readiness for environmental education of all categories of learners. Within the framework of the study, the dynamics of responses from the experimental and control groups were analysed to assess the impact of the developed programme on the formation of environmental literacy, attitudes towards inclusive education and readiness for inclusive practice. The findings demonstrated a significant positive shift in the experimental group: understanding of deep-seated environmental issues improved (increase of up to +12%), the frequency of demonstrating environmentally responsible behaviour rose (increase of up to +12%), a more positive attitude towards inclusion was formed (+32%), and self-assessed readiness to work in an inclusive context increased substantially (+56%). Analysis of the experimental group students' feedback revealed key positive aspects of the programme, such as the practical adaptation of visual materials, the development of tiered tasks, lesson modelling and the exploration of technical support tools. Among the suggestions for improvement, students highlighted the need for more practical work with children with disabilities, the necessity of internships in inclusive classrooms and a greater number of examples of adapted lessons. The data attest to the effectiveness of the developed programme in fostering key competencies of future teachers for inclusive environmental education. The findings contribute to the enhancement of educational programmes and methodological support for teacher training

Keywords: children's individual characteristics; adaptation; equal opportunities; children with disabilities; interactive sessions

INTRODUCTION

The current stage of societal development is characterised by an increase in global environmental problems, which necessitates the cultivation of a high level of environmental culture and a responsible attitude towards the environment in the younger generation. Primary school lays the foundation for environmental worldview and behaviour, which determines the importance of teachers' professional readiness to address these tasks. Concurrently with the environmental imperative, the educational landscape is actively evolving towards inclusion. The recognition of every child's right to quality education, irrespective of their individual characteristics and needs, makes it necessary to train

teachers capable of working effectively with diverse groups of learners, including children with disabilities (CwD).

The study of the formation of environmental competencies in future teachers, as well as the integration of an inclusive approach into teacher education, are areas that have attracted the attention of many researchers. V. Singh & A.K. Prajapati (2021) concluded that inclusive education entails creating an educational environment that ensures equal opportunities for the development and learning of all children, taking into account their uniqueness and needs, pointing out that co-education promotes the development of empathy, tolerance and collaborative skills.

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A.A. Adieva *et al.* (2025) believe that training teaching staff capable of integrating environmental education into the inclusive educational process is an important condition for ensuring the country's sustainable development and the social integration of all its citizens. The authors identified obstacles preventing teachers from integrating environmental education into the inclusive process, and also determined potential opportunities and resources to support this process. O. Mapako (2025), studying the formation of environmental competencies in primary school teachers in the context of inclusive education, argues that future teachers must possess methods for adapting environmental content and tasks for learners with various needs, as adaptation is important when teaching in an inclusive environment.

Researchers in the field of forming environmental competencies in future teachers, L. Oliveira *et al.* (2024), laid the foundations for the theory and methodology of environmental education in a pedagogical higher education institution, which include ecology as a science, the basics of natural history and nature conservation. In their conclusions, the authors defined the content of environmental knowledge, skills and values necessary for future teachers, and identified methods for cultivating students' environmental culture. The issues of environmental worldview and environmental responsibility in future teachers were investigated by N.N. Abdulah & M.S. Mahmud (2025), emphasising the importance of forming not only knowledge, but also deep convictions, value orientations and readiness for environmentally responsible behaviour. D. Nimante & M. Kokare (2022) proposed a model of teacher environmental competence and assessed the level of its development. As a result, the authors proved the necessity of forming holistic competencies enabling teachers to effectively solve professional tasks in the field of environmental education.

Research in the field of inclusive education and preparing teachers to work in an inclusive environment was conducted by F. İşcen-Karasu & D. Kayahan-Yüksel (2023), whose conclusions substantiated the need to create an accessible and supportive educational environment for all children, highlighting the importance of an individualised approach, collaboration between specialists and parents, as well as the specialised training of teachers to work in inclusive classrooms. A significant contribution to the development of the concept of inclusive education and the study of practical aspects of its implementation was made by A.T. Kebede, T.N. Phasha (2024). In the findings of their work, the authors focused on creating an inclusive culture in schools, developing inclusive pedagogy and using effective teaching strategies. However, the analysis of existing research has shown that insufficient attention has been paid to the issues of forming comprehensive environmental competencies in future primary school teachers specifically in the context of inclusion. Such aspects as the following remain underexplored: the development of specific methods and technologies for effectively integrating environmental education into the inclusive educational process; consideration of the individual characteristics of children with

disabilities when organising environmental activities; and the most effective forms and methods in an inclusive context.

Accordingly, the aim of this work was to analyse aspects of environmental competence development in future primary school teachers within the context of inclusion. To achieve this aim, the following objectives were set: to examine scientific approaches, models, and pedagogical technologies for fostering environmental competence in educators under inclusive education conditions; to identify the level of environmental competence development among students at I. Arabaev Kyrgyz State University and their understanding of inclusive education within an environmental context; and to determine the factors that facilitate the effective formation of environmental competence in future primary school teachers.

MATERIALS AND METHODS

The study employed a mixed-methods approach, combining qualitative and quantitative methodologies. This allowed for a comprehensive investigation of the students' level of environmental competence development and the specific features of its manifestation within the context of inclusive education. An analysis of works by C. Zalla & K. Yates (2021), M. Badawieh *et al.* (2024), and K.U. Alieva & A.S. Ismailova (2024) on the issues of environmental education, inclusive teaching, and teacher training was carried out to identify the content and structure of future teacher preparation.

The investigation into the level of environmental competence development under inclusive education conditions was conducted at I. Arabaev Kyrgyz State University from December 2024 to March 2025. It involved 50 third-year students (specialising in "Pedagogy and Methodology of Primary Education") aged up to 23 years (mean age – 21.5 years; 33 females and 17 males). Using random assignment, the participants were divided into an experimental group (EG) and a control group (CG), each comprising 25 individuals. The selection was based on voluntary written consent; individuals who violated the protocol, missed sessions, or withdrew their consent during the experiment were excluded from the sample. The procedure complied with ethical standards (National Health and Medical Research Council, 2007), ensuring anonymity and the right to withdraw from participation without any consequences. The dynamics of environmental literacy were assessed using an 8-item questionnaire (Table 1) administered before and after the experiment. The analysis of results was based on comparing the questionnaire responses (questions No. 1-2 – literacy, No. 5 – attitude towards inclusion, No. 6 – readiness, No. 7-8 – conditions for implementation) using descriptive statistics and qualitative synthesis. The formative face-to-face practical course (36 hours: 10 hours of theory, 16 hours of practice) for the EG focused on inclusion theory and laboratory practice in material adaptation. The CG underwent traditional training of an equivalent volume. Upon completion of the course, the EG students participated in a 4-item survey on the effectiveness of the training (Table 2).

Table 1. Questionnaire for assessing the level of environmental literacy

No.	Question	Answer option
1	What major environmental problems are you aware of? (Select no more than three)	a) environmental pollution (air, water, soil) b) climate change (global warming, greenhouse effect) c) biodiversity loss (extinction of plant and animal species) d) depletion of natural resources (shortage of water, minerals, forests) e) the waste problem (household, industrial) f) other (please specify)
2	Provide examples of environmentally responsible behaviour. (Select all applicable options)	a) resource conservation (water, electricity, heating) b) waste sorting and disposal c) responsible consumption (choosing eco-friendly goods, avoiding excess) d) care for nature (not littering, not harming plants and animals) e) participation in environmental campaigns and events f) environmental education of others g) other (please specify)
3	How can environmental activities involving children with diverse educational needs be organised? (Select all applicable answers)	a) individualisation of tasks, taking into account each child's pace and abilities b) use of hands-on work, games, observations, and various creative activities c) adaptation of materials (simplified texts, use of visual supports) d) work in small groups/pairs, taking into account different levels of preparedness e) creation of a supportive and safe environment f) organisation of excursions and hands-on activities in nature with due regard for accessibility g) use of information and computer technologies with adaptive capabilities h) involvement of specialists (special education teachers, psychologists) for consultations i) other (please specify)
4	What methods and techniques can be used to adapt environmental materials for children with SEN (Special Educational Needs)?	a) use of large font and clear illustrations b) provision of information in various formats (text, audio, video) c) use of visual materials (schemes, tables, pictures) d) simplification of instructions and texts, avoidance of metaphors and abstractions e) use of visual aids and hands-on tasks f) ensuring accessibility of the workplace and materials g) provision of additional time to complete tasks h) use of alternative assessment methods i) other (please specify)
5	Do you believe that environmental education can be effectively implemented in an inclusive classroom?	a) yes, absolutely b) probably yes c) probably no d) no, it is difficult e) I find it difficult to answer Open-ended response for obtaining qualitative data on motivation
6	How prepared do you feel to work with children with SEN within the context of environmental education?	a) prepared b) not fully prepared, lack knowledge c) unprepared d) lack practical experience
7	What difficulties might arise when implementing environmental education in an inclusive classroom? (Select all that you agree with)	a) insufficient foundational knowledge in natural sciences and ecology among children with SEN b) theoretical overload and lack of hands-on activities adapted for different needs c) teachers' insufficient mastery of inclusive environmental education methodologies d) difficulties in selecting and applying effective methods of teaching ecology to different categories of children e) lack of modern equipment, laboratories, and adapted materials f) lack of time for individual work with each child g) difficulties in interaction between children with different educational needs h) other (please specify)
8	What conditions are necessary for the successful implementation of environmental education in an inclusive classroom? (Select all applicable options)	a) adaptation of materials and teaching methods to accommodate different needs b) provision of an accessible educational environment (physical, informational) c) availability of necessary resources and equipment, including adapted materials d) flexibility and individualisation of the approach to teaching each child e) creation of a positive and supportive classroom climate (acceptance, support) f) support from and collaboration with specialists (special education teachers, psychologists) g) trained teachers (knowledge, skills in inclusion and environmental education) h) collaboration with parents (legal representatives) of children with SEN i) other (please specify)

Source: compiled by the author

Table 2. Questionnaire for determining the effectiveness of the programme in the experiment and students' readiness to work with children with SEN

No.	Question	Answer option	Question type
1	What new knowledge did you gain during the experimental programme?	Own answer	Open-ended
2	Which aspects of the programme were most useful to you?	Own answer	Open-ended

Table 2. Continued

No.	Question	Answer option	Question type
3	Which aspects of the programme could be improved?	Own answer	Open-ended
4	How would you rate your level of readiness to work with children with SEN within the context of environmental education after completing the programme?	a) ready b) rather ready c) not ready d) rather not ready	Closed-ended

Source: compiled by the author

The analysis of responses combined qualitative methods for examining students' detailed opinions and quantitative methods for summarising and presenting data from closed-ended questions, as well as the frequency of mentions in open-ended responses. To interpret the answers to questions No. 1-3, thematic analysis was applied with the aim of identifying key themes, ideas, and patterns within the students' extended responses. In order to determine the most prevalent opinions, the number of times specific themes or particular statements occurred in the students' answers was calculated. To summarise the responses to question No. 4, methods of descriptive statistics were employed, including the calculation of absolute and relative frequencies (percentages): determining the number and proportion of students who selected each response option.

RESULTS

Primary school constitutes the foundation for cultivating a caring attitude towards nature, the cornerstone for integrating environmental themes into the educational process. Within the framework of inclusive education, in a classroom where children with diverse educational needs learn together, environmental education assumes particular

importance. It not only imparts knowledge about nature but also fosters the development of social skills, the capacity for empathy, and a sense of responsibility. Inclusive education represents an educational philosophy aimed at establishing equitable learning conditions for all pupils, including those with special educational needs. The essence of this approach lies in the joint education of all children in mainstream educational settings, irrespective of their individual differences, be they physical, cognitive, social, emotional, linguistic, or other characteristics (Chhetri, 2025). The goal of inclusive education is not merely the mechanical placement of children within the same classroom, but the creation of an educational environment that accommodates the needs of each child, promotes their development and social integration, and cultivates in all learners a tolerant and respectful attitude towards differences. Ecology lessons in such a classroom help children to interact more effectively, teach them to work collaboratively, to consider the opinions of others, and to care for the surrounding world. Inclusive education, with its key principles – equity, accessibility, participation, and respect for the individuality of every child – creates a distinctive platform for developing environmental competencies in future teachers (Table 3).

Table 3. Principles of inclusive education and their connection to environmental competencies

Title	Description
Principle of equity	Requires consideration of the educational needs of all pupils, including those with special educational needs. Consequently, the process of developing environmental knowledge, skills, and convictions must be adjusted to account for the diversity of learners' perception levels and potential.
Principle of accessibility	Requires the creation of an educational environment in which every child can actively participate in the learning process, including environmental activities. This may involve the use of diverse methods and forms of work, the application of assistive technologies, and individual educational pathways.
Principle of participation	Underscores the importance of involving all learners in the educational process. In the context of environmental education, this means creating opportunities for collaborative research activities, project work, and discussion of environmental problems, which contributes to the development of communicative and social competencies alongside environmental ones.
Principle of value	Focuses primarily on the individuality of each learner and the necessity of considering their personal characteristics in the process of developing environmental awareness and a caring attitude towards the environment.

Source: compiled by the author based on M. Badawieh *et al.* (2024)

Environmental competencies constitute a complex of an individual's knowledge, skills, values, and attitudes that enable them to interact effectively with the environment, make environmentally responsible decisions, and carry out activities aimed at preserving nature and ensuring sustainable development. In other words, this is what a person knows, can do, and how they relate to issues of ecology and environmental protection, as well as their readiness and ability to act in accordance with environmental principles (Alieva & Ismailova, 2024). In the context of education, the environmental competencies of future teachers include

methodological competencies: the ability to organise and conduct lessons on environmental topics, taking into account the individual and age-related characteristics of pupils; the use of diverse methods and forms of work; and the assessment of the level of development of environmental knowledge and skills. It is worth noting that environmental competencies form an integrated system that allows an individual to be an environmentally literate, responsible, and active member of society.

Within the professional training of future teachers, three key components of environmental competencies

have been identified: the cognitive component – encompasses environmental knowledge (fundamental ecological concepts, laws of nature, the impact of human activity on the habitat, principles of sustainable development), an understanding of interconnections within ecosystems, and an awareness of environmental problems at regional, national, and global levels. The operational-activity component presupposes environmental skills and abilities, such as observing natural objects and phenomena, conducting simple environmental investigations, participating in nature conservation actions, and cultivating environmentally appropriate behaviour in everyday life and professional activity. It also includes methodological skills for organising environmental education for primary school children, particularly taking into account their special educational needs. The value-motivational component reflects the future teacher's environmental values, convictions, and attitudes, their responsibility for the state of the environment, their readiness for environmentally oriented professional activity, and their motivation to foster environmental culture in primary school children. This component also includes empathy towards living beings and an understanding of the importance of biodiversity conservation.

The formation of environmental competencies in future primary school teachers within the context of inclusive education is underpinned by a number of psychological theories. Albert Bandura's social learning theory (McLeod, 2025) has been advanced, which highlighted the importance of learning through observation and modelling, this being particularly effective in the development of environmental responsibility. Gardner's theory of multiple intelligences (Cherry, 2025) takes into account the diversity of learners' abilities and aptitudes. This theory enables the development of differentiated approaches to forming environmental competencies, taking into account the individual needs of children with disabilities. It is noteworthy that of particular importance for environmental education in inclusive settings is the concept of Universal Design for Learning, which proposes flexible approaches to teaching and accommodates the diversity of learners' needs, as well as ensuring equal access to education. Pedagogical science and practice have accumulated significant experience in the field of forming environmental competencies in future teachers. The analysis of existing models and approaches allows for the identification of several key directions and the determination of their potential and limitations in the context of inclusive education (Table 4).

Table 4. Models and approaches to developing environmental competences in education

Designation	Description	Advantages	Limitations in the context of inclusion
Subject-Centred Approach	Focuses on transmitting a system of environmental knowledge to students within discrete academic disciplines (e.g., biology, geography, chemistry). Environmental aspects are integrated into the content of these subjects.	Provides a robust theoretical foundation; fosters a systemic understanding of ecological processes and phenomena.	May prove insufficiently adapted to the diverse educational needs of students, particularly those with special educational needs. Additional methodological work on differentiation and individualisation of instruction is required. Does not always ensure the development of practical skills and a value-based attitude towards nature.
Interdisciplinary Approach	Involves integrating environmental issues into the content of various academic disciplines (not only natural sciences but also the humanities and socio-economic fields).	Promotes a holistic view of environmental problems, demonstrates their interconnectedness with various spheres of human activity, and develops systemic thinking.	Requires a high level of coordination among instructors from different disciplines. Developing integrated tasks and projects that accommodate diverse educational needs can present considerable difficulty.
Activity-Based Approach	Aims at the active participation of students in practical environmental activities: field research, environmental projects, volunteer initiatives, and the development of methodological materials for the environmental education of schoolchildren.	Facilitates the formation of practical abilities and skills, fosters initiative and responsibility, and enhances motivation to study ecology. Aligns well with the principles of inclusive education by allowing the forms and types of activities to be adapted to students' varying capabilities.	Requires meticulous organisation of practical activities, ensuring accessibility of the environment and materials for all students, and the design of differentiated tasks that account for varying levels of preparedness and ability.
Competence-Based Approach	Oriented towards developing not only students' knowledge but also their ability to apply it in professional practice to solve environmental problems. Identifies the key environmental competences essential for a future teacher.	Clearly defines learning objectives in the form of specific competences, ensures the link between theoretical preparation and practical activity, and enables the assessment of the level of environmental competence development.	Requires the development of diagnostic instruments and assessment tools that consider the diversity of students' educational needs. It is necessary to design an educational process that supports competence development at varying levels of complexity.

Table 4. Continued

Designation	Description	Advantages	Limitations in the context of inclusion
Socio-Ecological Approach	Emphasises the interconnection between social and environmental problems; cultivates in students an understanding of the social conditioning of ecological crises and the necessity of societal participation in resolving them.	Develops civic responsibility, forms readiness to participate in solving environmental problems at various levels, and promotes an understanding of the importance of inclusive approaches in environmental activity (engaging all members of society, including people with special educational needs).	May require additional training for instructors in the fields of social pedagogy and inclusive interaction. It is necessary to create conditions for the participation of all students in socio-ecological projects, taking into account their capabilities.
Pedagogy of Sustainable Development	Develops in future teachers an understanding of the principles of sustainable development and the ability to integrate them into the educational process. Particular attention is paid to issues of social justice, economic well-being, and environmental sustainability.	Forms a systemic, future-oriented worldview; promotes the development of critical thinking and the capacity for responsible decision-making. The inclusive dimension can be integrated through the examination of issues related to the accessibility of education and resources for all members of society.	Requires deep integration of sustainable development principles into curricula and programmes. Developing learning materials and tasks that accommodate diverse educational needs within the context of sustainable development can be a challenging undertaking.

Source: compiled by the author based on C. Zalla & K. Yates (2021)

The selection of the most appropriate methods and techniques for adapting environmental materials for children with disabilities depends on the specific nosology, developmental level, and individual characteristics of each child. The combination of factors that create favourable conditions for the successful formation of environmental competencies in all learners, including those with special educational needs, thereby contributing to the development of an environmentally responsible and inclusive society, exerts a positive influence on the process of forming environmental competencies within the field of inclusive education. These factors comprise the integration of environmental themes into the curriculum; relevance; adaptation and consideration of the special educational needs of all learners; the use of diverse teaching

methods; the creation of an inclusive educational environment; the active involvement of educators and their professional development; and engagement with parents and the local community.

Considering the significance of integrating environmental knowledge into the educational process, particularly for children with special educational needs, and drawing upon a set of key factors that create favourable conditions for the formation of environmental competencies, an experiment was conducted. A preliminary quantitative analysis of the responses from students in the experimental and control groups at Arbaev Kyrgyz State University prior to the experiment is presented in Table 5, which enabled an assessment of the initial level of development of the competencies under investigation.

Table 5. Questionnaire survey to determine the level of environmental literacy of students in the EG and CG before the experiment

Question No.	Responses	CG (No.)	EG (No.)
1	a) environmental pollution	18	15
	b) climate change	7	6
	c) biodiversity loss	5	4
	d) depletion of natural resources	3	2
	e) waste problem	10	8
2	a) resource conservation	15	13
	b) waste sorting and disposal	8	7
	c) responsible consumption	6	5
	d) careful treatment of nature	12	10
	e) participation in environmental campaigns	2	1
	f) environmental education and outreach	0	1
3	a) individualisation of tasks	2	1
	b) use of hands-on activities	5	6
	c) adaptation of materials	3	2
	d) work in small groups/pairs	4	3
	e) creation of a supportive environment	1	2
	f) excursions and practical activities	3	0
	g) use of ICT	6	6
	h) involvement of specialists	0	2

Table 5. Continued

Question No.	Responses	CG (No.)	EG (No.)
4	a) use of large print	7	5
	b) provision of information in various formats	4	3
	c) use of visual materials	6	6
	d) simplification of texts and instructions	5	5
	e) use of visual aids	8	8
	f) ensuring accessibility of the workstation and materials	2	3
5	a) yes, absolutely	3	2
	b) rather yes	10	8
	c) rather no	7	9
	d) no, it is difficult	3	4
	e) don't know / find it difficult to answer	2	2
6	a) I am ready	1	1
	b) not entirely ready, lack knowledge	9	11
	c) not ready	10	8
	d) lack practical experience	5	5
7	a) insufficient foundational knowledge base	2	1
	b) theoretical overload and lack of practical activities	5	6
	c) insufficient mastery of inclusive environmental education methodologies among teachers	4	3
	d) difficulties in selecting and applying effective teaching methods	6	7
	e) lack of modern equipment	9	10
	f) lack of time for individual work with each child	1	0
	g) difficulties in interaction between children with different educational needs	1	0
	h) other (please specify: __)	0	0
8	a) adaptation of materials and methods	2	3
	b) ensuring an accessible environment	6	6
	c) availability of necessary equipment	4	3
	d) individualisation of the approach to teaching each child	1	0
	e) creation of a positive and supportive climate in the classroom	6	7
	f) collaboration with specialists	2	6
	g) trained teachers	3	1
	h) cooperation with parents of children with disabilities	6	2
	i) other (please specify: __)		

Source: compiled by the author

The results of the initial questionnaire survey of students in the control and experimental groups prior to the experiment revealed an overall insufficient level of environmental literacy and readiness for inclusive environmental education. Both groups demonstrated some awareness of environmental pollution and waste issues; however, their understanding of systemic environmental problems, such as climate change and biodiversity loss, was poorly expressed. Among the examples of environmentally responsible behaviour, resource conservation and a caring attitude towards nature predominated, whereas active forms of participation, such as environmental campaigns and awareness-raising, were rarely mentioned. Awareness of inclusive teaching methods proved to be low, with such important aspects as individualisation and material adaptation scarcely noted. In the understanding of

adapting learning materials, references to visual aids and large print prevailed. The majority of students expressed doubts about their readiness to teach ecology to children with special educational needs and disabilities (SEND), citing a lack of knowledge and practical experience. Among the potential difficulties, a shortage of modern equipment and challenges in selecting effective teaching methods were identified, while the necessary conditions included ensuring an accessible environment and collaboration with parents. The data obtained confirm the need for implementing an experimental programme aimed at developing competencies in inclusive environmental education among future primary school teachers. The training programme in the experiment with students is based on methods and techniques for adapting environmental materials for children with SEND (Table 6).

Table 6. Programme content (thematic plan)

Session No.	Session Topic	Session Format	Session Procedure	Number of hours
1	Introduction to inclusive education and characteristics of children with SEND	Lecture-presentation	Studying the core concepts of inclusive education, the classification of SEND, and discussing the perceptual characteristics of children with various impairments	2

Table 6. Continued

Session No.	Session Topic	Session Format	Session Procedure	Number of hours
2	Principles and approaches to adapting learning materials for children with SEND	Seminar-discussion	Analysis of the principles of accessibility, individualisation, and sensory integration. Discussion of various approaches to adapting learning materials	2
3	Adaptation of visual environmental materials	Practical session	Analysis of examples of visual materials on ecology. Development and modification of illustrations, diagrams, and tables using colour coding and visual supports. Creation of accessible presentations; conducting a case study on adaptation	4
4	Adaptation of sensory environmental materials	Practical session	Exploring the use of tactile, auditory, and olfactory sensations in environmental education. Development of sensory bins and didactic materials with various textures; role-playing games	4
5	Simplifying and structuring text-based environmental information	Practical session	Analysis of complex environmental texts. Identification of key concepts. Exercises in simplifying sentences and structuring information using lists and diagrams. Creation of adapted texts; solving crosswords	2
6-7	Adaptation of interactive and hands-on environmental tasks	Practical session	Analysis of typical environmental experiments and observations. Development of adaptation options for children with visual and hearing impairments (using sound signals, tactile models, and verbal descriptions). Development of adaptation options for environmental games and project-based activities for children with musculoskeletal disorders and autism spectrum disorders (ASD) (using alternative means of participation, visual cues, structured tasks, and work with cards)	4
8	Use of assistive technologies in inclusive environmental education	Lecture-presentation	Overview of specialised software and applications, interactive whiteboards, and electronic resources that can be used to adapt environmental materials and support the learning of children with SEND	4
9	Development of differentiated tasks in ecology for children with SEND	Practical session	Development of a set of environmental tasks on the topic “The Water Cycle in Nature”, taking into account various levels of complexity and the educational needs of children with different types of SEND	4
10	Modelling an inclusive lesson in ecology	Practical session	Development of a script for a lesson segment in ecology using adapted materials and differentiated tasks to include children with various educational needs. Games. Presentation and discussion of the developed segments	4
11	Evaluating the effectiveness of adapted environmental materials	Seminar-discussion	Discussion of criteria for evaluating the effectiveness of adapted materials. Analysis of examples of assessing the academic achievements of children with SEND when using adapted materials. Reflection on the experience gained	2
12	Final assessment (defence of developed materials)	Presentation	Presentation and defence of the sets of adapted environmental materials and inclusive lesson segments developed by the students. Discussion and feedback	4

Source: compiled by the author

Within the framework of the experimental programme, students underwent training in adapting environmental materials for various nosological categories of children with disabilities (CwD), mastering specific techniques and methods tailored to each group: visual and tactile aids for children with visual impairments; visual materials and sign language for children with hearing impairments; structuring and sensory breaks for children with autism spectrum disorders (ASD); simplification and visualisation for children with intellectual disabilities; and ensuring accessibility alongside alternative means of task completion for children with musculoskeletal disorders (MSD). As a result of the training, students acquired practical skills in adapting and designing environmental materials, developing multi-level tasks, and planning inclusive ecology lessons supported by assistive technologies.

Upon completing the programme, students demonstrated increased readiness to work in an inclusive environment, deeper knowledge of the characteristics of CwD, the ability to apply adaptation principles, develop differentiated materials, and design inclusive ecology lessons, while exhibiting empathy and commitment to working with such children. Analysis of the theoretical frameworks indicated the effectiveness of combining activity-based and competence-based approaches, integrated with the principles of the socio-ecological approach and the pedagogy of sustainable development, for fostering environmental competencies in future primary school teachers within inclusive education settings. Analysis of the response dynamics of students in the control and experimental groups before and after the experiment revealed significant differences in the changes that occurred in both groups (Table 7).

Table 7. Indicators of awareness in the EG and CG after the experiment

Question No.	Answers	CG (No.)	EG (No.)
1	a) environmental pollution	18	22
	b) climate change	6	9
	c) biodiversity loss	5	6
	d) depletion of natural resources	1	3
	e) waste problem	11	9
2	a) resource conservation	15	16
	b) waste sorting and disposal	9	10
	c) responsible consumption	6	5
	d) caring attitude towards nature	10	12
	e) participation in environmental campaigns	3	4
	f) environmental education	0	2
3	a) individualisation of tasks	3	5
	b) use of hands-on activities	5	10
	c) adaptation of materials	4	12
	d) work in small groups/pairs	4	6
	e) creation of a supportive environment	2	9
	f) excursions and practical activities	3	6
	g) use of ICT	6	9
	h) involvement of specialists	2	5
4	a) use of large print	5	9
	b) presentation of information in various formats	6	6
	c) use of visual materials	4	8
	d) simplification of texts and instructions	5	5
	e) use of visual aids	8	10
	f) ensuring accessibility of the workspace and materials	2	5
5	a) yes, definitely	5	9
	b) rather yes	12	9
	c) rather no	2	2
	d) no, it is difficult	4	4
	e) I do not know / I find it difficult to answer	2	1
6	a) I am ready	1	15
	b) I am not fully ready, I lack knowledge	9	3
	c) I am not ready	10	2
	d) I lack practical experience	5	5
7	a) insufficient foundational knowledge	0	3
	b) theoretical overload and lack of practical activities	6	7
	c) insufficient command of inclusive environmental education methodologies among teachers	4	6
	d) difficulties in selecting and applying effective teaching methods	6	8
	e) lack of modern equipment	12	15
	f) lack of time for individual work with each child	0	0
	g) difficulties in interaction between children with different educational needs	0	0
	h) other (please specify: __)	0	0
8	a) adaptation of materials and methods	5	9
	b) ensuring an accessible environment	2	6
	c) availability of necessary equipment	5	9
	d) individualisation of the approach to teaching each child	1	6
	e) creating a positive and supportive classroom climate	5	9
	f) collaboration with specialists	1	6
	g) trained teachers	4	5
	h) collaboration with parents of CwD	6	6
	i) other (please specify: __)	0	0

Source: compiled by the author

Ecological literacy (questions 1 and 2). In the experimental group (EG), a more significant increase was recorded in the understanding of systemic environmental problems (climate change, biodiversity loss) and in the

frequency of responses reflecting an active environmental stance (participation in campaigns, awareness-raising). In the control group (CG), changes in these questions are negligible, and in some instances, a decline in indicators

is even observed. Attitudes towards Inclusive Education (question 5). The EG demonstrated pronounced dynamics towards a more positive perception of the feasibility of effective inclusive environmental education. The CG also exhibits a positive shift, albeit a less significant one.

Readiness for practical work (question 6). Self-assessment of readiness for practical work in an inclusive setting underwent fundamental changes in the EG, where the number of students confident in their readiness increased substantially. In the CG, the level of self-assessment remained virtually unchanged. Understanding of challenges and necessary conditions (questions 7 and 8). The EG exhibits a deeper awareness of the potential challenges of inclusion and a significant increase in the understanding of the necessary conditions for its successful implementation, including the adaptation of materials, ensuring accessibility, individualisation of instruction, and teacher preparation. In the CG, the dynamics in these questions are weakly expressed or absent. Comparative analysis demonstrates a pronounced positive effect of the experimental programme on ecological literacy, attitudes towards inclusion, and, most notably, on the self-assessed readiness for practical work within inclusive environmental education among EG students. In the CG, where instruction was conducted traditionally, no significant changes were recorded. This confirms the effectiveness of the developed experimental methodology.

Analysing student feedback on the experimental programme allows for the identification of a number of positive aspects that contributed to the development of their competencies in the field of inclusive environmental education. Students attached particular importance to practical sessions on adapting visual materials, noting their contribution to understanding the principles of creating accessible visualisations for children with various perceptual characteristics. Modules dedicated to the development of multi-level tasks proved useful for mastering a differentiated approach to teaching in an inclusive environment. The modelling of lesson segments provided a valuable opportunity for the practical application of acquired knowledge and for receiving constructive feedback. Information on assistive technologies for learning expanded students' knowledge of the resources available for working with children with special educational needs, and the study of the developmental characteristics of various categories of children with disabilities contributed to the formation of a more conscious approach to the teaching and learning process. The development of information transformation skills, particularly the ability to translate textual content into visual forms, as well as instruction in the principles of Universal Design, were noted as important acquisitions conducive to creating accessible learning materials. Furthermore, students expressed confidence in using tactile materials for studying nature with children who have sensory impairments and noted the development of skills in designing multi-level tasks that allow for the individual learning pace of each child to be taken into account.

Alongside the positive feedback, students put forward a number of suggestions for improving the programme. Five individuals pointed to a lack of practical training in interacting with children with disabilities and expressed a need for a greater number of practical sessions directly with this category of learners, as well as for the arrangement of visits and placements in operational inclusive educational settings. Another five students noted the necessity of providing a larger quantity of specific examples of adapted lessons on various environmental topics for different nosological groups. Three students expressed a wish for a list of supplementary resources and online platforms that facilitate inclusive education. Two individuals consider it important to place greater emphasis on developing empathy and emotional readiness for working with children with disabilities, while another two noted a certain overload of theoretical blocks, suggesting they be made more interactive and practice-oriented.

Analysis of the self-assessment of readiness levels for working with children with disabilities upon completion of the programme showed that a significant majority of students in the experimental group rated their readiness as fairly high: nearly half of the participants feel confident and competent, while another portion lean towards a positive assessment. However, a certain proportion of students still experience a lack of confidence in their readiness, and a small number feel unprepared (Fig. 1).

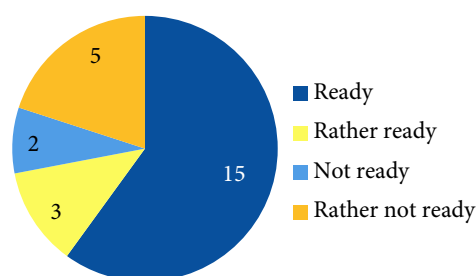


Figure 1. Self-assessment of the EG's level of readiness for working with children with disabilities upon completion of the programme

Source: created by the author

Thus, the training programme received an overall positive evaluation from students, who noted its contribution to the development of the requisite competencies. At the same time, the suggestions put forward indicate a need for further refinement of the programme, particularly by increasing the practical component, providing a greater number of specific examples and resources, and placing greater emphasis on the emotional aspects of working with children with disabilities. The data obtained represent valuable material for further analysis of the programme's effectiveness and for identifying avenues for its optimisation.

DISCUSSION

The conducted experimental study was aimed at identifying the effectiveness of the developed training programme

focused on fostering environmental competencies in future primary school teachers within the context of inclusive education. The experimental results demonstrated a statistically significant increase in the level of ecological literacy in the experimental group compared to the control group following completion of the developed training programme. This attests to the effectiveness of the proposed methodology, which included the adaptation of environmental materials and the use of inclusive pedagogical approaches. A questionnaire survey of experimental group students revealed their positive perception of the programme, its practical significance, and the utility of the proposed methods for adaptation and enhancing readiness to work in an inclusive classroom. The obtained results align with the findings of a number of researchers who underscore the effectiveness of targeted instruction in ecological literacy for future educators. I. Murni *et al.* (2023) in their study also noted a significant increase in the level of environmental knowledge and skills among teacher training students following the implementation of a specialised course emphasising practical activity and an interdisciplinary approach.

The findings of this study concerning the enhancement of future primary school teachers' readiness to work with children with disabilities through the implementation of a training programme emphasising the adaptation of environmental materials are corroborated by the work of A.G. Lugo (2024). The author's research indicates the necessity of embedding inclusive education issues directly within the process of developing future teachers' professional skills. The similarity of the conclusions lies in the assertion that targeted training, incorporating specific knowledge and skills related to inclusive practice, exerts a direct positive influence on the level of students' preparedness to work with children with disabilities. In particular, these results demonstrate that students who have undergone training with a focus on inclusion exhibit a high level of understanding of children's needs and greater confidence in their ability to adapt educational materials. However, it is important to note that the present study focused on a specific subject area – environmental education – and on a particular aspect of inclusive practice – the adaptation of educational materials – whereas the work of A.G. Lugo (2024) encompassed a broader spectrum of inclusive competences or a different subject context. Thus, the results of this study reinforce the author's argument in favour of the necessity of systematically embedding inclusive practices within the preparation of future teachers. They also demonstrate that, even within a specific subject area such as environmental education, the targeted development of relevant knowledge and skills significantly enhances students' readiness to work in an inclusive educational environment.

The data obtained in the study regarding the positive impact of the training programme on the formation of environmental competences in future primary school teachers find parallels in the work of B. Priyanga *et al.* (2022), which examined the influence of practice-oriented training on the development of these competences in future

primary school teachers. A key point uniting the results with the conclusions of the author and his colleagues is the confirmation of the significance of actively engaging students in the development of educational materials and the modelling of pedagogical situations. In the present study, the experimental group participants highly rated the practical sessions for children with disabilities, which directly implied their active involvement in the creation and transformation of educational content. Similarly, the research by B. Priyanga *et al.* underscored that when students are directly involved in the process of creating and applying pedagogical tools, their understanding of the subject and readiness for future professional practice increase significantly. The positive evaluation of the programme by students of Arabaev Kyrgyz State University, which emphasised the practical adaptation of materials, serves as further confirmation of the conclusions of B. Priyanga *et al.* (2022) that practical experience and the active role of the student in the learning process are key factors in the formation of sustainable professional competences, including in the field of environmental education.

The obtained data on the positive impact of the training programme are supported by the conclusions of the work of L. Lucassen *et al.* (2025). According to the authors' research, inclusion can have a positive effect on the academic outcomes of children with disabilities, provided that adequate support and resources are made available. The present study, although not directly focused on the academic results of children with disabilities themselves but rather on teachers' readiness to create conditions for their successful learning, indirectly confirms this interrelationship. The programme developed for the experiment was aimed at equipping future teachers with the competences necessary to provide adequate support and resources within the context of environmental education. The ability to adapt materials, employ differentiated approaches, and create an inclusive educational environment is a key factor in ensuring access to the learning process for children with disabilities and, consequently, in potentially improving their academic outcomes.

The results of the study resonate with the broader findings of the research by B.G. Stone & B. Saggars (2023), wherein the authors emphasised that the academic outcomes of peers without disabilities do not deteriorate in inclusive classrooms and may even improve owing to collaborative learning and diversity. Furthermore, the authors noted that inclusion fosters the social integration of children with disabilities, the development of their communicative skills, and a sense of belonging. When future teachers possess the requisite competences, they can more effectively stimulate interaction among all learners, promoting both academic growth and social integration. Thus, the present study contributes to establishing the pedagogical foundation for the positive effects of inclusion identified by B.G. Stone & B. Saggars (2023).

According to I.H. Yue Yim (2024), inclusion fosters the development of empathy and tolerance in all learners within

an inclusive setting and can lead to enhanced self-esteem and self-confidence in children with disabilities. The author considers that the key factors for successful inclusion are well-prepared teachers, methods of adaptation, and inclusive pedagogical technologies. Additionally, as indicated in the obtained results, teaching assistants (special education teachers, psychologists) and adapted educational materials and equipment are essential. It should be added that effective inclusion requires collaboration among teachers, parents, specialists, and school administration, where an atmosphere of acceptance, respect, and support plays a vital role.

The results of the present study, aimed at enhancing future primary school teachers' readiness for inclusive environmental education, should be considered within the context of the barriers to successful inclusion identified by J-W. Law *et al.* (2023), who highlighted such obstacles as insufficient funding and resources; inadequate training of teaching staff; insufficient accessibility of the educational environment; and stereotypes and prejudices regarding children with disabilities. Although the present study contributes to improving teacher preparation, it does not address systemic issues such as insufficient funding, limited resources, or existing stereotypes within society. Overcoming these barriers requires a comprehensive approach and concerted efforts at various levels – the school, the education system, and society as a whole. The conclusions of J-W. Law *et al.* underscored the need for further investigation of effective practices and the overcoming of existing barriers.

The tools for self-assessment and the development of inclusive practices, devised by V. Kumar *et al.* (2024), also underscore the importance of reflection and the continuous refinement of pedagogical approaches. By fostering future teachers' understanding of inclusion principles and practical adaptation skills, the programme in this experiment lays the groundwork for their ongoing self-assessment and professional growth in the field of inclusive education. Thus, the present study complements the work of V. Kumar *et al.* (2024), which proposes specific models and tools for implementing inclusive practices in schools.

Questions regarding the study of environmental competences within the context of inclusive education lie at the intersection of two important fields of pedagogical science and practice; consequently, there are fewer researchers engaged with this set of issues than in each of the fields individually. The work of Y. Herlanti *et al.* (2024) proposed practical methods of teaching and material adaptation and also provided examples of successful projects. This directly echoes the aim of the training programme in the present findings – to equip future teachers with specific skills and knowledge for adapting environmental content and organising inclusive environmental activities. The results of this study have empirically confirmed the necessity and effectiveness of preparing teachers for the integration of environmental education into inclusive education, thereby creating a basis for the development of key social and emotional skills in all learners through the exploration of the environment.

The study by M.J.N. Nalipay *et al.* (2023) focuses on the importance of fostering an understanding of the human-nature symbiosis for the development of preschool children with disabilities. The authors emphasised that practical interaction with nature contributes to the holistic personal development of such children. This finding directly aligns with one of the key aspects of the experimental curriculum: preparing future teachers to adapt environmental materials in consideration of sensory characteristics and to organise practical outdoor activities for children with disabilities. Having completed the programme proposed in this experiment, prospective teachers will be able to create learning situations in which children with various sensory needs actively interact with the environment, thereby forming an understanding of the interconnection between humans and nature, which, according to M.J.N. Nalipay *et al.*, is crucial for their comprehensive development.

T.C. Young & K. Malone (2023) investigated the development of social skills and empathy in children with disabilities in an inclusive setting and suggested that this has a direct bearing on the formation of the value-motivational component of environmental competencies, such as a responsible attitude towards nature and compassion for living beings. The authors stressed that direct experience with natural objects and phenomena is key to building environmental knowledge, skills, and values, particularly for children with disabilities. The findings of the present study – that, when educating future teachers, it is essential to design inclusive environmental lessons incorporating hands-on interaction with nature and material adaptation, thereby creating conditions conducive to the development of these very social and emotional aspects – are consistent with the authors' conclusions. As in the present research, the study by A.J. Tinedo Rodríguez (2020) indicates that the adaptation of teaching materials, methods, and forms of work is an indispensable condition for the successful inclusion of children with disabilities in environmental education. Environmental projects and collaborative outdoor activities can foster communication, cooperation, and a sense of belonging among all learners.

In their study, V. Lamanauskas & R. Makarskaitė-Petkevičienė (2023) asserted that environmental education, particularly within an inclusive context, holds significant potential for cultivating children's empathy for living beings and a sense of responsibility for the state of the environment. The results of the present research empirically confirmed and concretised this proposition, as well as the notion that purposeful environmental education indeed contributes to the formation of a deep emotional connection with nature in learners and serves as a foundation for developing empathy. In this experiment, this manifested in the positive dynamics of future teachers' attitudes towards environmental issues and their readiness for environmentally responsible behaviour following the completion of the developed training programme.

At the same time, certain aspects of the present study diverge from findings reported by other scholars. For instance, the study by A.S. Widodo *et al.* (2024) demonstrated

only a weak influence of standard ecology lectures on students' practical readiness to work in an inclusive context. The more notable positive outcomes in the present study may be attributed to the programme's focus on the practical adaptation of materials and students' active participation in the learning process. The results of this study may also somewhat diverge from the conclusions of N. Mousavi *et al.* (2024), who, while examining the impact of specific visualisation methods on the acquisition of environmental knowledge by children with disabilities, pointed to the necessity of a more differentiated approach to the selection of visual aids. In the present findings, the adaptation of visual materials was considered within a broader context, which could have led to generalised positive results that require further in-depth investigation into the efficacy of particular visual techniques for different categories of children with disabilities.

No significant studies were identified that explicitly oppose the integration of environmental education issues within the context of inclusive education in the preparation of future primary school teachers. The majority of contemporary pedagogical research underscores the importance of cultivating both environmental culture and readiness for inclusion in future educators as integral components of their professional competence. However, it can be posited that some authors may indirectly express reservations or point to potential challenges associated with such integration. For example, the study by J.J. Kayombo *et al.* (2025) focused exclusively on an in-depth examination of specific methods for working with particular categories of children with disabilities, without devoting sufficient attention to the environmental content of instruction. The work by M. Jaime *et al.* (2021), which was solely dedicated to environmental education, did not address the specifics of working within an inclusive classroom. Nevertheless, the overarching trend in pedagogical science is directed towards identifying effective pathways for integrating various facets of teacher professional preparation, including environmental education and inclusive practices, to ensure quality education for all children.

Overall, the data obtained corroborated the conclusions of many leading researchers who have noted the pivotal role of practical orientation and the inclusion of inclusive education issues in teacher training. The minor discrepancies with the findings of certain studies may serve as a point of departure for future research that delves deeper into the specifics of adapting environmental content for diverse groups of children with disabilities and into ways of optimising the integration of environmental and inclusive education within pedagogical preparation.

CONCLUSIONS

This study investigated the formation of environmental competencies in future primary school teachers within the

context of inclusive education. The experiment confirmed the effectiveness of the developed programme aimed at building skills in adapting environmental materials for inclusive classrooms. The implementation of a lecture and practical course on mastering methods for modifying visual, sensory, and textual content ensured a statistically significant increase in environmental literacy in the experimental group compared to the control group. In the experimental group, the following results were obtained: environmental literacy (up to a 12% increase in understanding of key issues and responsible behaviour), a more positive attitude towards inclusive environmental education (+32% in the selection of positive responses), and an increase in self-assessed readiness to work in an inclusive context (+56%), in contrast to the control group, where changes were minimal or insignificant. The majority of students in the experimental group positively evaluated the practical orientation of the programme, highlighting the benefits of adapting visual materials, designing multi-level tasks, and modelling lessons. A significant outcome was the acquisition of skills in handling visual and tactile information, as well as the principles of Universal Design. Despite this, some students (5 individuals) noted an insufficient number of practical sessions involving children with disabilities and a need for internships, as well as for additional lesson examples (5 individuals) and resources (3 individuals), which indicates directions for the further development of the programme. The obtained results attest to the effectiveness of the developed training programme in fostering the requisite competencies in future primary school teachers.

The small student sample constitutes one of the limitations of the present study, which may affect the comprehensiveness of the reflection of their actual readiness for practice. Furthermore, no long-term observation was conducted regarding the application of the acquired knowledge and skills by graduates in their professional activities. Future exploration of this topic could include a comparison of the effectiveness of different methods of integrating inclusive issues into the training of teachers of various subjects, as well as an analysis of the impact of training educators to adapt environmental content on the dynamics of academic achievement among children with disabilities in inclusive classrooms.

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Virtual laboratories and the development of students' creative freedom in Singapore

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Abstract. The purpose of the study was to assess the influence of sandbox environments on the development of students' experimental thinking. The methodology of the study included a case study of the functioning of Virtual Reality/Augmented Reality laboratories and Design-Based Research for the design, implementation, and improvement of a VR/AR sandbox environment in the educational process. The study established that in Singapore, within leading universities, including the National University of Singapore and Nanyang Technological University, virtual reality and augmented reality were integrated into the system of practice-oriented learning as a full educational and research environment. Examples of this practice include digital twin and three-dimensional modelling laboratories, the Virtual Interactive Human Anatomy, Virtual and Augmented Reality for Structures, and LeARNus projects, and XR simulation environments for training specialists to act in emergency situations. In these environments, students complete interdisciplinary projects, create their own digital products, model professional scenarios, and test them in conditions close to reality, which supports learning through activity and practical experience. The results of the experimental study, performed in three cycles of Design-Based Research, indicated a gradual increase in all indicators. In the first cycle, the average level of competence development was observed, including creative experimentation ($M = 2.5$) and problem solving ($M = 2.9$), which corresponded to the stage of adaptation to the virtual and augmented reality environment. In the second cycle, after the improvement of the learning design, a marked improvement was recorded, including navigation skills ($M = 3.8$) and task completion (84%), together with a decrease in cognitive errors. In the third cycle, the highest results were achieved, with creative experimentation increasing to $M = 4.7$, problem solving to $M = 4.6$, and task completion reaching 92%, which confirmed the formation of a high level of digital and creative competencies. The practical value of the study lies in the possibility of using its results by teachers, higher education institutions, and educational technology developers to implement and improve learning environments using virtual and augmented reality, aimed at developing students' creative and professional competencies

Keywords: learning tasks; digital technologies; sandbox environment; practice-oriented learning; technical navigation skills

INTRODUCTION

Virtual laboratories were becoming increasingly widespread in the higher education system of Singapore, providing students with opportunities to perform experiments, model professional situations, and implement their own creative ideas in a digital learning environment. The use of virtual and digital technologies and augmented and virtual reality tools supports the development of creative freedom, independence, critical thinking, research skills, and the ability to search for non-standard solutions. The education system of Singapore was oriented towards innovative development and the implementation of modern learning technologies, which creates favourable conditions

for forming students' creative potential. This determines the relevance of examining the use of virtual laboratories as a means of developing students' creative freedom in higher education institutions in Singapore.

Extending the understanding of creative freedom in education systems, B. de Paula (2024) analysed the motivations and experiences of East Asian master's students at an elite university in the United Kingdom. The researcher drew attention to the tension between academic requirements and the desire for creative self-expression, which affects students' professional development. For this reason, virtual laboratories in Singapore appear as environments

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that reduce these constraints by providing flexibility and freedom in individual learning trajectories. Similar ideas were supported by M. Jones *et al.* (2025), who analysed international online interaction between students in laboratory learning between the United States and the United Kingdom. The researchers showed that joint digital work deepens understanding of complex scientific processes and stimulates collective problem solving. In this format, virtual laboratories become spaces where creative freedom was realised through communication, exchange of ideas, and the joint construction of knowledge.

X. Geng & Y. Su (2024), through a meta-analysis of metaverse integration into STEM (Science, Technology, Engineering, Mathematics) education, demonstrated that immersive technologies strengthen creativity and cognitive activity among learners. The researchers emphasised that digital environments support the modelling of complex phenomena without physical constraints. For this reason, virtual laboratories in Singapore, built according to metaverse principles, broaden the possibilities for creative experimentation and scientific inquiry. The further development of this idea was traced in the work of D. Mishra *et al.* (2023), which analysed activity-based online learning. Active student participation in the educational process supports deeper acquisition of knowledge and the development of independence. In virtual laboratories, this was manifested as students' ability to construct learning actions independently, which directly supports their creative freedom. L. Nahar & C. Machado (2025) examined inquiry-based learning and the development of 21st-century skills, emphasising the importance of independently formulating questions and testing hypotheses. This approach was shown to form the critical and creative thinking required for modern education. In virtual laboratories in Singapore, this was implemented through a safe environment in which students can freely test their own ideas and research assumptions. In parallel, H. Qawaqneh *et al.* (2023) analysed the influence of artificial intelligence in virtual laboratories on motivation to learn mathematics. Adaptive systems increase students' engagement and interest and individualise the educational process. This creates conditions in which creative freedom was expressed through the choice of different task-solving strategies and personalised educational routes.

Continuing the topic of technological integration, T. Paul & M. Rohil (2025) compared virtual laboratories and augmented reality in work-integrated learning. Noted that despite certain implementation challenges, these technologies have considerable potential for combining learning and practice. In this format, virtual laboratories expand students' creative opportunities in professionally oriented tasks. A separate dimension of creative freedom was examined in the study by J. Tejada *et al.* (2023), which created an educational space at the intersection of creativity, electroacoustic music, and digital competencies. A high level of student engagement and the importance of interdisciplinary interaction were emphasised. In virtual

laboratories, such approaches support the integration of art and technology and strengthen creative self-expression. H. Yu & J. Wang (2025) systematically analysed the influence of virtual reality on the development of students' creativity. The researchers demonstrated that VR (Virtual Reality) technologies strengthen imagination, innovative thinking, and the capacity for experimentation. For this reason, virtual laboratories in Singapore that use VR solutions create an environment in which students freely create, model, and test new ideas without spatial or material constraints.

Despite the aspects addressed by these researchers, gaps remained in the insufficient attention paid to the long-term influence of virtual laboratories on the development of students' creative freedom in Singapore. The integration of different digital technologies into a single educational ecosystem and their influence on the formation of stable research and creative skills also remain insufficiently examined. The purpose of the study was to determine the influence of environments using virtual and augmented reality on the formation and development of students' experimental thinking during their learning activities. The objectives of the study were to identify practices of using virtual and augmented reality in the educational process, evaluate the dynamics of creative freedom development in a VR/AR (Augmented Reality) sandbox environment, and formulate patterns of learning behaviour during interaction with immersive technologies.

MATERIALS AND METHODS

The work had a mixed research design, which provided an in-depth analysis of the functioning of VR/AR laboratories in the natural conditions of the educational process. The case-study method was used for a comprehensive analysis of VR/AR laboratories as an educational environment for developing students' creativity. Within the case study, the empirical materials included VR/AR laboratories, learning tasks, and students' creative projects completed in an interactive environment. The main attention was focused on the sequence of the educational process, from students' familiarisation with the environment and completion of basic simulation tasks to the creation of their own creative digital products. The source base consisted of National University of Singapore (n.d.), Nanyang Technological University (n.d.), Keio-NUS CUTE Center (n.d.a), and National University of Singapore, Department of the Built Environment (n.d.). The features of using Digital Twin (n.d.), HTC VIVE (n.d.), and Microsoft (n.d.) technologies were identified. The visual material in the study was presented only as photo and screenshot documentation reflecting different stages of work. In particular, the interfaces of VR/AR laboratories during the completion of learning tasks were recorded (NUSNEWS, 2023), along with working moments of students interacting with digital simulations (Ellern, 2024) and the results of completed creative projects in the form of 3D models, virtual scenes, and interactive solutions (Keio-NUS CUTE Center, n.d.b).

The study was performed from September 2025 to May 2026 according to the Design-Based Research methodology at higher education institutions in Singapore, the National University of Singapore (NUS) and Nanyang Technological University (NTU), which involved consecutive cycles of designing, implementing, evaluating, and improving the educational environment. The study involved 68 second- and third-year students in Educational Technology, Computer Science, Information Engineering and Media, and Mechanical Engineering enrolled at one higher education institution, namely the National University of Singapore. The inclusion criteria were regular class attendance, absence of previous systematic experience with VR/AR sandbox environments, basic digital competencies, and written consent to participate in the study. The exclusion criteria were missing more than 20% of classes, refusal to participate at any stage of the study, and failure to complete compulsory practical tasks. The study used one experimental group without a control group, which corresponded to the principles of Design-Based Research. This approach enabled repeated improvement of the learning environment after each cycle of testing, analysis of the results obtained, and repeated implementation of updated learning solutions. Experimental thinking was measured using Lawson's Classroom Test of Scientific Reasoning (LCTSR) (PhysPort, n.d.), which assesses the ability to formulate and test hypotheses, plan an experiment, control variables, analyse cause-and-effect relationships, and interpret the results obtained. The comparison was made between the initial, intermediate, and final assessment results of the same participants. Student's paired samples t-test was used for assessment, allowing the indicators of the same students to be compared across three consecutive cycles.

Practical work was conducted twice a week over 24 teaching weeks. In total, 48 classes of 90 minutes each were implemented. Each class included a short theoretical introduction (10-15 minutes), practical experiments in the VR/AR sandbox environment (55-60 minutes), collective discussion of results (10-15 minutes), and reflection with completion of electronic observation journals (10 minutes). During the classes, students created their own virtual models, changed experimental parameters, tested alternative scenarios, analysed the consequences of their own decisions, completed individual and group projects, developed prototypes of digital objects, and presented the results of their work. Design-Based Research included three consecutive cycles. The first cycle was aimed at testing the basic version of the VR/AR sandbox environment and identifying user difficulties. The second cycle involved implementing an improved version of the environment. After the analysis of the first-stage results, the number of open experimental tasks was expanded, additional modelling tools were integrated, the possibility of varying the parameters of virtual experiments was provided, and the level of student independence during research tasks was increased. The third cycle involved using the final version of the environment to complete complex creative projects requiring

independent experiment planning, hypothesis testing, and reasoned presentation of results.

Assessment was performed on a five-point scale (1-5 points), where 1 point corresponded to the lowest level and 5 – to the highest level of formation of each defined criterion. The assessment criteria included the ability to formulate a research problem, propose and test hypotheses, independently plan an experiment, vary model parameters, analyse cause-and-effect relationships, interpret results, propose alternative solutions, and justify one's own conclusions. All research procedures complied with the ethical principles of voluntariness, confidentiality, anonymity, and academic integrity. Participants were informed in advance about the purpose of the study, the procedure for using the data obtained, and the right to stop participating at any stage without negative consequences. The study was performed according to the principles of the Declaration of Helsinki on ethical principles for research involving human participants (World Medical Association, 2013). Patterns of students' interaction with the VR/AR sandbox environment were identified, from guided task completion to independent modelling. The limitations of the study were related to the use of one experimental group without a control sample, the implementation of the study within one university, and the specific nature of the VR/AR infrastructure, which may limit the generalisation of the results to other educational contexts.

RESULTS

In Singapore, VR/AR laboratories have become part of the university ecosystem of practice-oriented learning, in which digital technologies were used not as a separate learning tool but as an environment for completing interdisciplinary projects, modelling professional situations, and developing students' creative thinking. This approach was based on the concept of learning by doing, according to which knowledge acquisition occurred through direct interaction with digital objects, experimentation, and the creation of students' own solutions. The laboratories of the National University of Singapore (NUS) and Nanyang Technological University (NTU) became leading centres for the development of such technologies, where learning spaces combine virtual (VR), augmented (AR), and mixed reality with modelling systems, 3D visualisation, artificial intelligence, and digital twins.

A specific feature of the Singaporean model was that students work not only with ready-made VR/AR applications but also create their own digital products. Learning tasks were built around real professional problems that require the design of interactive scenarios, development of three-dimensional models, programming of user interaction with digital objects, testing of interfaces, and evaluation of the effectiveness of created solutions. In most cases, the work was conducted in teams that include students from different specialties, which ensures the integration of engineering, design, pedagogical, and information competencies. The final stage of each project was the presentation of

the completed digital product and its testing in conditions as close as possible to professional practice (Nolan, 2021).

At the National University of Singapore, the VARS (Virtual and Augmented Reality for Structures) project became widespread for training students in construction and design specialities. Learning tasks included visualising structural elements of buildings, modelling loads, examining deformations, and analysing load-transfer paths. Using mobile devices, students superimposed three-dimensional digital models on real campus structures, analysed structures directly in the real environment, completed interactive exercises, and took thematic quizzes. In particular, the environment supported independent research activity by allowing experiments to be repeated many times and different variants of structural solutions to be tested without material costs (National University of Singapore, Department of the Built Environment, n.d.). For medical students, the VIHA (Virtual Interactive Human Anatomy) VR platform was used. In the virtual space, students interacted with high-precision three-dimensional models of the human body, changed the position of organs, analysed relationships between anatomical structures, completed interactive exercises on assembling separate body systems, and passed practical scenarios. Unlike traditional work with anatomical

specimens, the digital environment allowed unlimited repetition, return to previous stages, and an individual learning trajectory, which improved students' spatial thinking (Keio-NUS CUTE Center, n.d.b).

At Nanyang Technological University, interactive VR/AR laboratories were oriented towards students' creative projects in computer graphics, design, digital media, and engineering. Students created virtual historical reconstructions, AR applications for museums, crisis-modelling systems using drones, digital simulations of production processes, interactive learning games, and multimedia environments. Projects were completed in a problem-oriented learning format, where students had to propose their own technological solution to a real social or production problem. The work ended with public demonstrations, presentations, and assessment of the functionality of the created digital products, which combined creative activity, research work, and professional training (Nanyang Technological University, n.d.). Table 1 summarises the results of the analysis of students' work in VR/AR laboratories of higher education institutions in Singapore during learning projects and reflects the dynamics of development of technical, cognitive, and creative competencies during the staged implementation and improvement of VR/AR educational environments.

Table 1. Analysis of students' work in VR/AR laboratories of higher education institutions in Singapore during learning projects

Higher education institution (Singapore)	Real VR/AR laboratory	Elements of the educational environment	Examples of learning tasks	Results of students' projects
National University of Singapore (NUS)	5G AR/VR/BIM-XR Lab	Digital Twin environment interface, HTC Vive and XRSPACE VR headsets, HoloLens 2, AR tablets, and students' work with digital twins of buildings	Development of digital twins, AR visualisation of buildings, and VR modelling of engineering objects	3D building models, campus digital twins, and interactive VR scenes for architecture and construction
National University of Singapore (NUS)	Immersive Reality Lab	Students' work with spatial interfaces, testing of VR/AR applications, the process of creating simulations, and evaluation of user experience	Development of educational VR simulations, creation of spatial interfaces, and integration of generative AI into XR	Interactive VR applications, AR solutions, educational simulators, and prototypes of spatial applications
Nanyang Technological University (NTU Singapore)	Centre for Augmented and Virtual Reality (CAVR)	Interfaces of AR/VR development software, the modelling process, the use of modern XR equipment, and students' teamwork	Creation of VR learning environments, AR visualisation of technical processes, and development of digital content	Virtual learning laboratories, interactive 3D scenes, AR demonstrations, and XR prototypes
Nanyang Technological University (NTU Singapore)	School of Art, Design and Media – Interactive Media and 3D Animation Labs	Student workstations, interfaces of 3D-modelling software, and the process of creating digital content and animation	Development of 3D models, digital animation, and interactive media projects	3D animation, digital scenes, interactive multimedia projects, and VR content

Note: BIM (Building Information Modelling), XR (Extended Reality), CAVR (Centre for Augmented and Virtual Reality), AI (Artificial Intelligence), 3D (Three-Dimensional), and 5G (Fifth Generation Mobile Network)

Source: compiled by the author based on the analysis of National University of Singapore (n.d.), Nanyang Technological University (n.d.), Digital Twin (n.d.), HTC VIVE (n.d.), Microsoft (n.d.)

The analysis of cases indicated that the VR/AR laboratories of leading universities in Singapore ensure the integration

of modern digital technologies with practice-oriented learning. The educational process was aimed at completing

project tasks and developing digital, creative, and team competencies, while the outcome of learning activity was the creation of completed digital products for professional use. In Singaporean universities, including the National University of Singapore (NUS) and Nanyang Technological University (NTU), VR/AR laboratories operate where students work in virtual and mixed environments, creating simulations, digital twins, and interactive learning projects for engineering, medicine, and design. Their purpose was to develop practical and creative skills through immersive learning, where students not only use technologies but also create their own VR/AR solutions and research projects to solve real professional tasks. Figure 1 illustrates an XR simulation learning environment for training rescuers within the “Training boost for emergency responders through XR” project (National University of Singapore, Singapore), where realistic emergency scenarios were modelled to develop professional response skills.

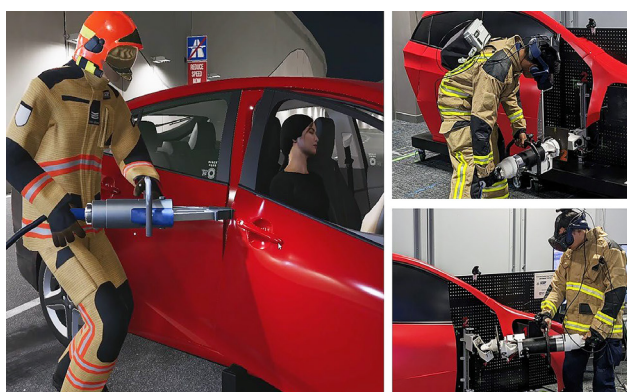


Figure 1. XR simulation environment for training rescuers within the “Training boost for emergency responders through XR” project (NUS, Singapore)

Source: compiled by the author based on NUSNEWS (2023)

Within the “Training boost for emergency responders through XR” project (NUS in cooperation with Singapore Civil Defence Force and HTX), students of the National University of Singapore were involved in developing and testing XR simulations for rescuer training. Participated in creating emergency scenarios, setting up VR/AR environments, and checking user interaction with the digital and physical elements of simulations. In addition to technical development, students acted as testers and analysts, assessing the effectiveness of training procedures and the quality of immersion in the immersive environment. The project was aimed at improving the quality of professional training for emergency services through the use of XR technologies that combine virtual and real components of learning (NUSNEWS, 2023). Figure 2 summarises the environments of VR/AR laboratories and forms of students’ project activity in Singaporean universities, where interactive technologies were used to create digital simulations, interdisciplinary projects, and innovative learning solutions within practice-oriented learning.



Figure 2. VR/AR laboratory environments and students’ project activity at NUS and NTU universities in Singapore
Source: compiled by the author based on J. Ellern (2024)

In Singaporean universities, including NUS and NTU, VR/AR laboratories function as integrated educational and research environments where students learn through immersion in virtual simulations of real professional situations. These laboratories were equipped with VR/AR headsets, spatial tracking systems, sensory interfaces, digital twin platforms, and 3D visualisation systems, which enable complex objects and processes to be modelled in real time. Within the educational process, students complete practical tasks in virtual environments, including engineering modelling, architectural design, urban systems simulations, medical training, and crisis-situation scenarios where decisions must be made under conditions of limited time and information. Figure 3 presents the LeARNus student AR platform, developed at the National University of Singapore (NUS), which was intended for creating interactive learning environments and converting learning materials into augmented reality within educational and project tasks.

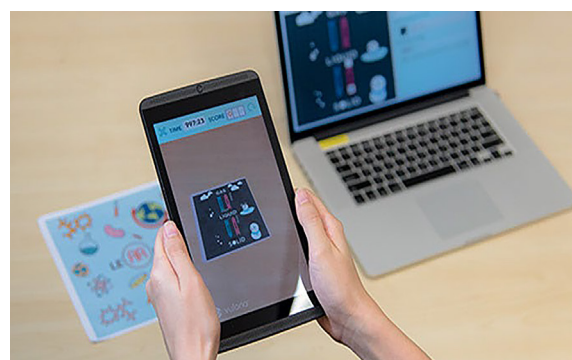


Figure 3. The LeARNus student AR platform for creating interactive learning environments at NUS
Source: compiled by the author based on Keio-NUS CUTE Center (n.d.a)

The LeARNus student platform was created within the Keio-NUS CUTE Center at the National University of Singapore (NUS) by a joint team of students and

researchers in computer science, HCI (human-computer interaction), and educational technology. The purpose of the development was to create a simple tool that allows teachers and students to create augmented reality (AR) learning scenarios without complex programming, transforming traditional learning materials into interactive 3D/AR objects that can be used in museums, schools, and university laboratories to increase engagement and develop active, experimental learning. The effectiveness of VR/AR sandbox environments in modern education was determined not only by the quality of visualisation of

learning material but also by the capacity to create conditions for active interaction, experimentation, spatial modelling, and decision-making in a safe digital environment. For this reason, assessment of the effectiveness of such technologies requires a comprehensive analysis of changes in students' technical, cognitive, and creative characteristics. Table 2 summarises the results of students in cycle 1 (initial implementation of the VR/AR sandbox environment), reflecting the level of formation of technical, cognitive, and creative skills at the stage of initial adaptation to the VR/AR educational environment.

Table 2. Results of students in cycle 1 (initial implementation of the VR/AR sandbox environment)

Indicator	Mean (M)	Standard deviation (SD)	Min-Max	% high level (≥ 4.0)
Technical navigation skills	3.1	0.62	2.0-4.0	18
Task completion (%)	72%	9.4	55-85%	22
Understanding of learning concepts	3.0	0.58	2.0-4.0	15
Problem solving	2.9	0.65	2.0-4.2	12
Creative experimentation	2.5	0.70	1.8-3.8	8
Team interaction	3.2	0.60	2.1-4.2	20
Cognitive errors (reverse scale)	3.8	0.55	2.5-4.5	-

Source: compiled by the author based on the study

In the first cycle of implementing the VR/AR sandbox environment, a predominantly average level of formation of the indicators under study was observed. The lowest values were recorded for creative experimentation ($M = 2.5$) and problem solving ($M = 2.9$), which indicated students' limited ability to use the tools of the environment independently without clearly structured instructions. The level of understanding of learning concepts ($M = 3.0$) and technical navigation skills ($M = 3.1$) remained average, reflecting the initial stage of adaptation to the VR/AR environment.

The task-completion rate was 72%, which confirmed the presence of difficulties in working with new digital tools. Team interaction ($M = 3.2$) was somewhat higher than other parameters, indicating the compensation of individual difficulties through group work. The high level for most indicators did not exceed 20%, and a considerable share of cognitive errors ($M = 3.8$ on the reverse scale) indicated the need to improve the structure of the learning environment. Table 3 summarises the results of students in cycle 2 (improved VR/AR sandbox environment).

Table 3. Results of students in cycle 2 (improved VR/AR sandbox environment)

Indicator	Mean (M)	Standard deviation (SD)	Min-Max	% high level (≥ 4.0)
Technical navigation skills	3.8	0.55	2.8-4.6	52
Task completion (%)	84%	7.2	70-95%	63
Understanding of learning concepts	3.7	0.52	2.9-4.7	55
Problem solving	3.5	0.60	2.5-4.6	48
Creative experimentation	3.4	0.63	2.3-4.5	45
Team interaction	3.8	0.50	3.0-4.7	60
Cognitive errors (reverse scale)	2.9	0.60	2.0-4.0	-

Source: compiled by the author based on the study

In the second cycle, after the improvement of the VR/AR sandbox environment, a marked improvement was recorded in all indicators under study. The greatest increase occurred in technical navigation skills ($M = 3.8$) and task completion (84%), which indicated students' greater confidence in working with digital tools. The indicators of understanding learning concepts ($M = 3.7$) and team interaction ($M = 3.8$) improved markedly, reflecting the effectiveness of interactive and group learning formats. The level of problem solving ($M = 3.5$) and creative

experimentation ($M = 3.4$) demonstrated a transition to more independent learning behaviour and initial manifestations of creative activity. The share of students with a high level of results increased to 45-63% depending on the indicator, which indicated the levelling of learning achievements in the group. Cognitive errors also decreased ($M = 2.9$), confirming increased adaptation to the environment and the effectiveness of the learning design. Table 4 summarises the results of students in cycle 3 (final VR/AR sandbox environment with open projects).

Table 4. Results of students in cycle 3 (final VR/AR sandbox environment with open projects)

Indicator	Mean (M)	Standard deviation (SD)	Min-Max	% high level (≥ 4.0)
Technical navigation skills	4.5	0.45	3.5-5.0	88
Task completion (%)	92%	5.8	80-100%	92
Understanding of learning concepts	4.4	0.48	3.6-5.0	85
Problem solving	4.6	0.44	3.8-5.0	90
Creative experimentation	4.7	0.40	3.9-5.0	95
Team interaction	4.5	0.46	3.7-5.0	87
Cognitive errors (reverse scale)	1.9	0.50	1.0-3.0	-

Source: compiled by the author based on the study

In the third cycle, which involved the use of the final version of the VR/AR sandbox environment with open creative projects, the highest indicators were recorded for all criteria. Creative experimentation reached the maximum value ($M = 4.7$), which indicated students' formed ability to create digital solutions independently and model alternative scenarios. High results were also obtained for problem solving ($M = 4.6$), navigation skills ($M = 4.5$), and team interaction ($M = 4.5$), reflecting the effective integration of technical and social competencies. The task-completion rate increased to 92%, and the share of students with high results exceeded 85-95% for most indicators. The cognitive error indicator decreased to the minimum level ($M = 1.9$), indicating stability of learning activity and effective acquisition of material. Overall, the results of the third cycle confirmed the formation of a high level of students' digital, cognitive, and creative competencies in the VR/AR sandbox-learning environment.

According to the assessment results obtained with Lawson's Classroom Test of Scientific Reasoning (LCTSR), a consistent increase in students' experimental thinking was recorded across the three stages of the study. At the initial stage, the mean result was 12.8 ± 2.9 points out of 24, which corresponded mainly to a transitional level of scientific thinking. After the intermediate learning cycle, the indicator increased to 16.4 ± 2.7 points, which indicated a marked improvement in students' ability to formulate hypotheses, plan experimental procedures, control variables, and analyse cause-and-effect relationships. At the final stage, the mean result reached 19.1 ± 2.4 points, demonstrating the formation of most components of experimental thinking at a high level. Statistical analysis using Student's paired samples t-test confirmed the reliability of differences between the initial and intermediate stages ($t = 8.47$, $p < 0.001$), between the intermediate and final stages ($t = 6.18$, $p < 0.001$), and between the initial and final assessments ($t = 14.36$, $p < 0.001$). The largest increase was noted for the indicators of variable control, hypothesis testing, and interpretation of experimental results, pointing to the development of skills for scientific research according to the logic of experimental cognition.

Overall, the results of the experiment, performed over three cycles of Design-Based Research in the VR/AR sandbox environment, indicated a stable positive dynamic in the development of students' technical, cognitive, and creative competencies. The transition from the

initial stage with predominantly average indicators and a high number of errors to the final cycle with a high level of independence, creative experimentation, and effective problem solving confirmed the effectiveness of staged improvement of the learning environment. The most pronounced growth was observed in creative activity, the ability to design independently, and team interaction, which indicates the formation of students' innovative thinking skills and effective work in virtual environments. The decrease in cognitive errors and the increase in task completion further confirmed the effectiveness of the implemented learning model, oriented towards practical activity and open projects in VR/AR laboratories.

The development of students' creative freedom within the experiment took place gradually through the staged complication of tasks in the VR/AR sandbox environment, from structured instructional exercises in the first cycle to partially open tasks in the second cycle and fully open project solutions in the third cycle. Changes were assessed through criterion-based evaluation of the level of creative experimentation, analysis of digital products created by students, and pedagogical observation of the degree of independence in choosing scenarios, tools, and ways of solving tasks in the virtual environment. Quantitative indicators were also recorded, including the level of creative experimentation, the number of alternative solutions, and project complexity, which allowed the growth of students' creative autonomy to be established during the consecutive improvement of the learning design.

As a result of the study, patterns of students' interaction with the VR/AR sandbox environment were identified, reflecting a gradual transition from the completion of structured learning actions to independent design of digital objects and scenarios. The analysis of activity demonstrated that the process of mastering the environment had a staged character, and changes in modes of interaction occurred as practical experience accumulated, spatial thinking developed, and confidence in the use of digital tools increased. At the initial stage, most students relied on step-by-step instructions, examples of task completion, and teacher recommendations. The exercises were characterised by strong dependence on external guidance, and each subsequent action was carried out only after the correctness of the previous operation had been checked. For example, when creating a three-dimensional model of a classroom, students initially only repeated the proposed

sequence of actions: adding basic geometric objects, scaling, changing textures, and arranging elements according to a ready-made example.

After students mastered the basic principles of working with the environment, a transition to the stage of adaptive use of digital possibilities was observed. Students began to change individual model parameters, experiment with colour schemes, lighting, the physical properties of objects, and variants of their interaction. While only instructional tasks were completed at the beginning, students later introduced their own modifications to the proposed projects. For example, when developing a VR model of a historical monument, some groups independently added information panels, interactive viewing points, sound accompaniment, or animation effects, although these elements were not included in the initial requirements. The next pattern was the formation of research behaviour. Students increasingly used the sandbox environment as a space for testing their own hypotheses, rather than only completing the assigned task. Before creating the final version of a model, numerous experiments were performed with the configuration of the environment, object scales were changed, the operation of interactive elements was checked, and different variants of user navigation were tested. For example, when creating a virtual biology laboratory, students tested several ways of arranging equipment, assessing the convenience of user movement in the space and the speed of completing laboratory procedures.

A separate pattern was the gradual increase in the number of project-improvement iterations. While the first works were completed after one execution cycle, most students later returned repeatedly to the models had created, correcting errors, changing the architecture of the space, or improving individual functional components. This approach indicated the development of skills for reflective analysis of their own activity. For example, after testing a VR quest, a group of students independently changed the system of transitions between rooms, reduced the number of information messages, and optimised user movement trajectories, which made the scenario more logical and understandable. Further development was characterised by a transition to independent modelling of complex educational products. Students began to work not with individual objects but with completed digital environments that combined three-dimensional graphics, interactive mechanisms, multimedia content, and learning scenarios. For example, during a project to create a virtual museum, thematic exhibitions, interactive information stands, navigation systems, and gamification elements were developed, allowing visitors to follow a learning route in different sequences.

The analysis also revealed a change in the character of interaction between students. At the initial stages, discussions concerned mainly technical difficulties in using software, while later communication focused on design solutions, the pedagogical appropriateness of created models, and ways of increasing the effectiveness of learning interaction. For example, when developing an AR

application for studying anatomy, students jointly analysed which interactive functions would support better acquisition of the material, discussed the optimal placement of information elements, and considered ways of visualising complex biological processes. In particular, the result was the formation of the ability to transfer acquired skills to new situations. After completing several learning projects, students no longer needed detailed instructions for new tasks, independently determined the sequence of work, selected digital tools, and predicted possible difficulties. For example, after creating a VR model of a classroom, implemented an interactive production laboratory project without additional consultations, using similar principles of spatial organisation but with completely different content.

The final pattern was the emergence of creative modelling, when the digital environment was no longer perceived only as a tool for completing a learning task and became a platform for implementing students' professional ideas. Independently initiated the creation of additional functions, proposed alternative ways of user interaction with the environment, and integrated elements of artificial intelligence, adaptive assessment systems, or team-interaction mechanisms. For example, some projects included interactive virtual assistants that provided hints to users depending on their actions, or adaptive learning routes that changed according to the success of previous stages. The combination of the identified patterns confirmed the regular development of students' interaction with the VR/AR sandbox environment from reproductive completion of learning operations to autonomous design of complex digital educational solutions, reflecting the formation of creative freedom, a research style of thinking, and readiness to use modern immersive technologies in future professional activity.

DISCUSSION

The implementation of virtual laboratories in the educational process in Singapore was accompanied by stronger manifestations of students' creative freedom, expansion of the range of independent decisions during experimental tasks, and increased variability of approaches to solving learning problems. Learning situations built on digital laboratory simulations created conditions for more flexible thinking, experimentation with parameters, and rapid hypothesis testing. The results obtained were consistent with the conclusions of Q. Aini (2023), who demonstrated that the implementation of individualised learning models supports freedom in constructing knowledge and stimulates independent creation of learning strategies. In leading universities in Singapore, virtual and augmented reality were integrated into the system of practice-oriented learning as full sandbox environments. Students work in VR/AR laboratories, creating digital twins, simulations, and interactive learning products. In parallel, the observed effects correlated with the study by R. Ardiansah & Z. Zulfiani (2023), in which interactive electronic materials aimed at developing creative thinking demonstrated the capacity to activate idea

generation and the formation of non-standard approaches to environmental tasks. Similar interactive approaches increase engagement in experimental activity, which subsequently expands the range of creative solutions during task completion. The results of the experiment demonstrated a gradual increase in all indicators under study across three cycles of VR/AR sandbox-environment implementation. In the first cycle, creative experimentation was $M = 2.5$, problem solving $M = 2.9$, technical navigation skills $M = 3.1$, and task completion – 72%, which corresponded to an average level of competence development. The data were consistent with the conclusions of S. Asare *et al.* (2023), who compared traditional laboratories with virtual environments and noted the advantages of digital platforms in increasing access to experimental activity. The absence of physical constraints enables more frequent modelling of alternative experimental scenarios. The results of the study aligned with the findings of A. Asmarany *et al.* (2023) that the use of Adobe Animate in creating virtual laboratory tools strengthened students' creative thinking. A similar increase in creative activity during interaction with interactive simulations was traced.

Certain parallels were identified with the approach of L. Corazza *et al.* (2022), who considered transformative learning through sustainable development and emphasised the role of reflective practices in forming critical thinking. Virtual laboratories create conditions for reflection on experimental actions, which strengthens the depth of analytical processes. The study by R. Fitri *et al.* (2024) demonstrated the effectiveness of project-based learning for developing students' creativity. It was stated that combining virtual laboratories with project tasks increases the generation of innovative solutions and supports the formation of interdisciplinary thinking. The data were in agreement with the conclusions of R. Hasibuan & A. Azizah (2023), demonstrating that the use of artificial intelligence in personalised learning supports students' creative development. Digital laboratory systems with adaptive elements also provided individualisation of experimental activity. Similar patterns were confirmed in the work of V.K. Kolil & K. Achuthan (2024), where virtual chemistry laboratories increase experimental awareness and practical skills. A similar increase in confidence in conducting experiments through simulation environments was identified. The study by O. Laseinde & D. Dada (2024) emphasised the role of virtual reality in STEM education. The results obtained confirmed that immersion in a VR environment stimulates the expansion of imagination and the creation of alternative models of experimental thinking. The conclusions of H. Lin & Q. Chen (2024) on the influence of AI-integrated applications on students' creativity and emotional perception of learning were reflected in the collected data. Increased emotional engagement and activation of creative responses were observed during work with digital laboratories. The results were consistent with the study by G. Reginald (2023), where virtual laboratories strengthen self-regulation of learning activity. Growth was

recorded in the ability to plan experiments and control the learning process. R. Reyes *et al.* (2024) described the use of virtual laboratories for experiential learning, with attention to advantages and difficulties. The authors confirmed advantages in forming creative solutions, although the need for pedagogical support was also noted to prevent superficial use of simulations. This correlated with the results of C. Sarapak *et al.* (2025), where agreement was shown regarding the increase in learning effectiveness through 3D virtual laboratories. The use of three-dimensional simulations was found to strengthen students' ability to model learning processes spatially.

Within the analysis, the influence of pedagogical approaches on the formation of creative skills in a digital environment was traced. The results paralleled the conclusions of E. Sari *et al.* (2023), who demonstrated the connection between project-based learning and the development of creative skills. It was underlined that project-oriented tasks combined with virtual laboratories strengthen manifestations of students' creative thinking. In the second cycle, a marked improvement was recorded: creative experimentation increased to $M = 3.4$, problem solving to $M = 3.5$, navigation skills to $M = 3.8$, and task completion – to 84%. In the study by S. Vuk (2023), the development of creativity in education was explored through active learning methods. The study confirmed that digital laboratories serve as environments of active interaction that stimulate creative actions. The approach of B. Wang & P. Li (2022) to digital creativity in STEM (Science, Technology, Engineering and Mathematics) education was confirmed in the collected data, where digital tools acted as a catalyst for creative thinking. A similar increase in the generation of alternative solutions was traced. The data were supplemented by the conclusions of Y. Wulandari *et al.* (2024), where the “Merdeka Belajar” model supports freedom of learning and creativity. In the third cycle, the highest results were achieved, with creative experimentation reaching $M = 4.7$, problem solving $M = 4.6$, navigation skills $M = 4.5$, and task completion increasing – to 92%, indicating a high level of formation of students' digital and creative competencies. Expansion of students' autonomy in choosing ways to complete tasks was traced. The results corresponded to the conclusions of X. Weng *et al.* (2022), who noted that digital project creation in STEM contributes to the development of students' creative thinking and strengthens the effectiveness of problem-oriented learning in digital environments. The use of virtual laboratory tools in combination with project activity increases students' ability to generate non-standard solutions and deepens their engagement in the learning process. The conclusions were consistent with the study by Z. Xing & Y. Qi (2022) on the role of interactive technologies in developing creativity through collaboration. The use of interactive tools in group tasks ensured a more active exchange of ideas and the formation of collective creative solutions. The position on folklore-based learning, where emphasis was placed on giving students freedom to choose learning strategies and increasing their autonomy, was aligned with

the approaches of A. Agung *et al.* (2024). The researchers established that educational practices oriented towards cultural content expand opportunities for self-expression and creative interpretation of material. The results of the study indicated that digital educational environments, including virtual laboratories, provide conditions for developing creative thinking and increasing the autonomy of learning activity. Expansion of the variability of solutions and activation of collective forms of interaction during learning tasks were traced.

CONCLUSIONS

In Singapore, within leading universities, specifically the National University of Singapore and Nanyang Technological University, virtual and augmented reality technologies were integrated into the system of practice-oriented learning as a full educational and research environment. Examples of this practice include digital twin and three-dimensional modelling laboratories, projects such as Virtual Interactive Human Anatomy, VARS, and LeARNus, and XR simulation environments for training specialists to act in emergency situations. In these environments, students not only use ready-made digital solutions but also create their own projects, model professional situations, develop interactive learning products, and test them in conditions close to reality, which forms the basis of learning through activity and experience.

The results of the experimental study within three cycles of Design-Based Research demonstrated a stable positive dynamic in the development of students' competencies. In the first cycle, an average level of technical and cognitive indicators was recorded as follows: creative experimentation ($M = 2.5$) and problem solving ($M = 2.9$), which reflected the adaptation stage of interaction with the virtual environment. In the second cycle, after the improvement of the learning design, a marked increase

in all indicators was observed, including navigation skills ($M = 3.8$) and task completion (84%), together with a decrease in cognitive errors. In the third cycle, the highest results were achieved, with creative experimentation increasing to $M = 4.7$, problem solving to $M = 4.6$, and task completion reaching 92%, denoting the formation of stable digital and creative competencies.

The analysis of students' interaction with the VR/AR environment identified a number of patterns in the development of learning behaviour. A gradual transition was established from reproductive following of instructions to adaptive use of digital tools, then to a research approach with hypothesis testing, and finally to autonomous design of complex educational products. Growth in work iterativity, development of reflection, a shift in communication from technical difficulties to discussion of design and pedagogical solutions, and the formation of creative modelling as the leading mode of activity were also observed. The results obtained confirm that VR/AR laboratories effectively support the development of creative freedom, experimental thinking, and students' readiness for innovative professional activity in the digital environment. Prospects for further research include expanding the sample, conducting comparative analysis of different types of virtual and augmented reality, and examining their long-term influence on the development of students' creative, cognitive, and professional competencies in different fields of education.

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AI tutors and emotional support to reduce academic stress among students at Spanish universities

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Abstract. The study aimed to assess how digital tutoring systems with emotional support functions affect students' academic stress in the context of Spanish higher education. The study was conducted using a quasi-experimental design with pre-and post-tests in the control and experimental groups. Initial measurements revealed a prevalence of moderate and high levels of academic stress among the study participants. Following the conclusion of the experiment, a reduction in academic stress, academic anxiety and emotional exhaustion was observed in the experimental group, whilst no significant changes were found in the control group. In the experimental group, the proportion of students with high academic stress decreased from 33.3% to 12.5%, while the mean stress score fell from 3.69 to 2.81 points. A high level of agreement was found between algorithmic recognition of emotional state and students' self-assessments, amounting to 86.3%. The highest ratings were given to the functions explaining the learning material, step-by-step recommendations and brief emotional check-ins. A statistically significant inverse relationship was found between the regularity of artificial intelligence tutor use and the level of academic stress (Pearson's correlation coefficient $r = -0.62$; $p < 0.001$). Regression analysis showed that the greatest contribution to reducing academic stress came from the regularity of digital tutor use, the initial level of academic stress, and trust in the recommendations of artificial intelligence systems. The practical significance of the study lies in substantiating the feasibility of using AI tutors and emotional support systems to support students' independent study, reduce academic stress and improve digital support within the university educational environment

Keywords: personalised learning; mood recognition; learning anxiety; emotional exhaustion; self-regulation; digital tools

INTRODUCTION

Universities were increasingly using artificial intelligence (AI) tutors to personalise learning, provide prompt feedback and support students' independent study. However, academic workload, deadlines, assessment and the need for constant self-organisation remain sources of stress that affect students' motivation to learn, their engagement and their ability to work effectively on educational tasks. There was therefore a need to examine whether AI tutors can fulfil a supportive role in the learning process and contribute to students' emotional self-regulation. Exploring this topic makes it possible to determine the feasibility of integrating mood recognition algorithms and digital emotional support into university learning platforms as a means of reducing academic stress.

In the academic literature, the issue of using artificial intelligence in higher education has been examined from various perspectives. P. González-Rico & M. Lluch

Sintes (2024) had reported that combining personalised mentoring with artificial intelligence tools contributed to the development of self-organisation, communication and responsible decision-making skills. The authors noted that personalised recommendations enabled students to manage their study workload more effectively and adapt more quickly to the demands of the educational environment. A. Hajeer *et al.* (2024) had examined students' perceptions of artificial intelligence tutors in higher education institutions in Spain and Hungary. The data revealed that the majority of participants viewed the possibility of receiving prompt feedback and personalised recommendations positively. Another aspect had been highlighted by H. Galindo-Domínguez *et al.* (2024), who had recorded a high level of readiness among Spanish educators to use artificial intelligence tools. The researchers concluded that the greatest potential of such technologies lay in the personalisation

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of the educational process and the adaptation of learning content to students' individual characteristics. J.-M. Agudo-García *et al.* (2025) had summarised the results of numerous studies on the use of artificial intelligence in higher education. The authors noted that the most consistent positive results were observed in the areas of personalised learning, automated student support and educational data analytics. The study by L.M.G. Gallastegui & R.R. Forradellas (2024) had demonstrated that predictive artificial intelligence models enabled the forecasting of learning difficulties and risks of academic failure. The study's findings had indicated the possibility of early identification of students requiring additional support. The authors had emphasised the importance of integrating predictive mechanisms into digital educational systems.

A systematic review by J.P. López-Goyez *et al.* (2024) had demonstrated a steady increase in the number of studies devoted to intelligent learning systems. A synthesis of the available findings showed that such systems contributed to improved learning outcomes and greater personalisation of the educational process. S.E. Vaca Zambrano *et al.* (2025) had reported a positive impact of personalised learning on students' engagement with the educational process. The findings indicated an improvement in individual learning pathways and an increase in the level of academic engagement. However, the authors did not examine the link between personalisation and students' emotional state. D. Rodríguez Cairo & Y. Ramírez Echavarría (2023) had found that the use of intelligent tutoring systems was accompanied by an improvement in the quality of academic support and the availability of advisory assistance. The researchers noted a reduction in response times to learning enquiries and improved access to educational resources. The main focus, however, was on educational outcomes rather than the psychological consequences of using such technologies. A study by H.H. Ariza (2026b) had demonstrated that the introduction of artificial intelligence tutors contributed to greater personalisation of learning and increased the effectiveness of educational interaction. The author concluded that adaptive recommendations enabled students to plan their own learning activities more effectively. The question of how such solutions had affected levels of academic stress remained outside the scope of the analysis. J.R. Hernández-Herrera *et al.* (2026) had found that AI-based adaptive learning systems allowed for a more flexible approach to addressing students' individual educational needs. The results demonstrated an increase in the level of personalisation and an improvement in indicators of learning interaction. At the same time, the authors did not investigate the potential for using emotional state analysis algorithms in an educational setting.

The analysis carried out showed that previous studies had predominantly focused on the personalisation of learning, adaptive student support mechanisms, the prediction of educational outcomes, and the evaluation of the effectiveness of AI tutors. Issues relating to academic stress, emotional well-being and the functioning of mood recognition algorithms in higher education were considered much less frequently. The interrelationships between the use of AI tutors, digital emotional support and changes in students' academic stress indicators remained understudied. Furthermore, there was limited empirical data on the effectiveness of integrating the educational and support functions of artificial intelligence into the university environment in Spain.

The aim of the study was to determine the impact of AI tutors with emotional state recognition and digital emotional support functions on the level of academic stress among university students in Spain. To achieve this aim, the following research objectives were set: to characterise the sample of study participants and establish the baseline level of academic stress among students; to determine the impact of AI tutors and emotional support systems on indicators of academic stress, academic anxiety and emotional exhaustion; to evaluate the effectiveness of mood recognition algorithms, identify patterns in the use of AI support functions, and determine the factors associated with a reduction in students' academic stress.

MATERIALS AND METHODS

The study used a quasi-experimental design with pre- and post-testing in experimental and control groups from March to May 2026. The eight-week experiment involved 240 full-time undergraduate students aged 18-24 from the Universidad Complutense de Madrid, the Universitat de Barcelona and the Universidad de Valencia. Participants used university learning platforms and provided informed consent. Students receiving psychological treatment or regularly using AI tutors were excluded. Each university recruited 80 students, who were allocated to groups by university, year of study and specialisation. The experimental group used Khanmigo (n.d.), Wysa (n.d.) and Woebot Health (n.d.) at least three times weekly, while the control group used standard digital resources. AI use was measured through platform logs.

Empirical data were collected using two author-designed questionnaires. The first measured academic stress, academic anxiety and emotional exhaustion; the second was completed after the experiment and assessed satisfaction with AI tutors and digital support. Internal consistency was checked using Cronbach's alpha: $\alpha = 0.84$ and $\alpha = 0.87$, respectively. The first questionnaire included socio-demographic items and statements on stress, anxiety, exhaustion and independent study (Table 1).

Table 1. Academic stress questionnaire used in the study

Statement	Measured indicator
I find it difficult to start working on academic tasks without external assistance.	Learning autonomy
A large number of deadlines creates a constant feeling of pressure.	Academic stress

Table 1. Continued

Statement	Measured indicator
I experience strong anxiety before examinations or tests.	Academic anxiety
I find it difficult to maintain concentration while completing academic tasks.	Concentration
I tend to postpone major assignments until the last days before the deadline.	Procrastination
My academic workload causes emotional fatigue.	Emotional exhaustion
After several hours of studying, find it difficult to remain productive.	Cognitive fatigue
I confidently plan and organise my study time.	Self-organisation
I quickly recover my ability to concentrate after intensive studying.	Self-regulation
The learning process was often accompanied by a feeling of psychological exhaustion.	Psychological exhaustion

Source: compiled by the author

All statements were assessed on a five-point Likert scale, from 1, “strongly disagree”, to 5, “strongly agree”. Higher scores indicated greater expression of the measured indicator. The survey was completed remotely through digital forms on university learning platforms after informed consent had been provided. The

baseline questionnaire was administered before the intervention and took about 12 minutes. After eight weeks, all students completed the same questionnaire again. The experimental group also assessed the usefulness of Khanmigo (n.d.), Wysa (n.d.) and Woebot Health (n.d.) functions (Table 2).

Table 2. AI support satisfaction questionnaire used in the study

Statement	Measured indicator
Khanmigo explanations helped understand learning material more quickly.	Perceived usefulness of academic explanations
Step-by-step recommendations made it easier to complete complex tasks.	Task-structuring support
Wysa emotional check-ins helped assess my current emotional state.	Emotional self-assessment
Wysa recommendations helped restore concentration during studying.	Concentration recovery
Dialogues with Woebot Health helped better understand the causes of academic tension.	Emotional reflection
Using digital tutors reduced the time needed to find relevant information.	Time efficiency
I trusted the recommendations generated by artificial intelligence systems.	Trust in AI recommendations
The use of AI made the organisation of learning more convenient.	Learning organisation
I am willing to use such systems in my further studies.	Intention to continue use
Overall, it was satisfied with the use of AI support.	Overall satisfaction

Source: compiled by the author

Statistical analysis included absolute and relative frequencies, means, standard deviations and 95% confidence intervals. Pre- and post-test indicators were compared using the paired t-test or, where normality was not confirmed, the Wilcoxon test. Between-group differences were assessed using the Mann-Whitney U-test and Fisher’s exact test. Pearson’s coefficient was used for correlation analysis, and multiple regression with Wald’s test was applied to examine selected predictors. Statistical significance was set at $p < 0.05$. Agreement between AI-based emotion recognition and students’ self-assessments was calculated in the experimental group. Four categories were used: calm, stressed, anxious and emotionally exhausted. Matching AI and student classifications were expressed as a percentage of all completed check-ins. Participants also rated academic explanations, step-by-step recommendations, emotional check-ins, reflective dialogues and motivational messages on a five-point usefulness scale. The study followed the Code of Ethics of the American Sociological Association (2025), the ICC/ESOMAR International Code of Conduct for Market, Public and Social Research and Data Analysis (2025) and the Guidelines on Ethics and Data Protection (European Commission, 2021). Participation was voluntary and required electronic informed consent.

Students received information on the study purpose, duration, collected data and withdrawal rights. Personal data were anonymised before analysis, and results were reported in aggregated form. The study was limited to three Spanish universities, an eight-week intervention and self-report measures, which were considered when interpreting the results. The study was limited by the inclusion of students from three Spanish universities, the eight-week intervention period and the use of self-report questionnaires.

RESULTS AND DISCUSSION

Baseline characteristics of the sample and indicators of academic stress among students

The initial stage of the study focused on the composition of the sample and the baseline measurement of academic stress, academic anxiety and emotional exhaustion before the introduction of AI-based support tools. The study included 240 students enrolled at three Spanish universities. For further analysis, the overall sample was distributed according to year of study, academic specialisation and study group. Students from the three universities were allocated equally between the experimental and control groups: each institution contributed 40 students to the experimental group and 40 students to the control group (Table 3).

Table 3. Distribution of study participants by year of study, academic specialisation and study group

Variable	Category	N	%
Year of study	First year	58	24.2
	Second year	61	25.4
	Third year	63	26.3
	Fourth year	58	24.2
Academic specialisation	Education	72	30.0
	Psychology	56	23.3
	Humanities	58	24.2
	Social Sciences	54	22.5
Study group	Experimental group	120	50.0
	Control group	120	50.0
Total sample	All participants	240	100.0

Source: compiled by the author

The distribution of participants showed that all years of study and academic specialisations were represented in the sample. First-year students accounted for 58 participants (24.2%), second-year students for 61 (25.4%), third-year students for 63 (26.3%) and fourth-year students for 58 (24.2%). By academic specialisation, the largest group consisted of students enrolled in Education programmes, with 72 participants (30.0%). Psychology programmes were represented by 56 students (23.3%), Humanities by 58

students (24.2%) and Social Sciences by 54 students (22.5%). The experimental and control groups each comprised 120 participants. The mean age of the students was 20.8 years ($SD = 1.7$). Before the intervention, the baseline indicators of the experimental and control groups were compared. This comparison was conducted to determine whether the groups had similar initial levels of academic stress, academic anxiety and emotional exhaustion before the use of AI-based academic and emotional support tools (Table 4).

Table 4. Baseline indicators of academic stress, academic anxiety and emotional exhaustion in the experimental and control groups

Indicator	Experimental group M (SD)	Control group M (SD)	p-value
Academic stress	3.69 (0.60)	3.65 (0.62)	>0.05
Academic anxiety	3.60 (0.57)	3.56 (0.58)	>0.05
Emotional exhaustion	3.22 (0.55)	3.20 (0.56)	>0.05

Note: values were presented as mean scores and standard deviations on a five-point Likert scale. Differences between the experimental and control groups were not statistically significant at $\alpha = 0.05$

Source: compiled by the author

The baseline values showed no statistically significant differences between the experimental and control groups. This indicated that both groups had comparable initial indicators of academic stress, academic anxiety and emotional exhaustion before the intervention. Therefore, subsequent changes could be analysed without attributing them to unequal starting conditions. Following the baseline comparison of the experimental and control groups, the overall distribution of participants according to levels of academic stress was examined. The analysis showed that academic stress was widespread among the students included in the study. More than half of the participants demonstrated a moderate level of academic stress (51.7%, $n = 124$), while nearly one-third exhibited a high level of academic stress (32.5%, $n = 78$). In contrast, only 15.8%

of students ($n = 38$) were classified as having a low level of academic stress. The predominance of moderate and high stress levels indicated that academic stress represented a common feature of the students' educational experience at the beginning of the study. These findings characterised the baseline condition of the sample prior to the implementation of AI-based academic and emotional support tools and provided a reference point for evaluating subsequent changes during the intervention. The next stage of the baseline analysis concerned the academic activities most often associated with stress. The assessment included deadlines and accumulation of assignments, examination preparation, difficulties in self-organisation, interaction with instructors and work in academic groups (Table 5).

Table 5. Structure of academic stress factors at the initial stage

Academic stress factor	Mean score (M)	SD
Deadlines and accumulation of assignments	4.12	0.58
Examination preparation	3.94	0.63
Difficulties in self-organisation	3.51	0.67

Table 5. Continued

Academic stress factor	Mean score (M)	SD
Interaction with instructors	2.83	0.71
Work in academic groups	2.67	0.74

Note: scores were presented as mean values on a five-point Likert scale, where 1 indicates the lowest manifestation of the factor and 5 indicates the highest. SD = standard deviation

Source: compiled by the author

The highest mean scores were recorded for deadlines and accumulation of assignments ($M = 4.12$; $SD = 0.58$), examination preparation ($M = 3.94$; $SD = 0.63$) and difficulties in self-organisation ($M = 3.51$; $SD = 0.67$). Lower scores were recorded for interaction with instructors ($M = 2.83$; $SD = 0.71$) and work in academic groups ($M = 2.67$; $SD = 0.74$). These results showed that academic stress at the initial stage was mainly associated with the organisation of individual learning activity, preparation for assessment and the distribution of workload before deadlines. After the baseline stage, students in the experimental group were provided with access to AI-based academic and emotional support tools. Khanmigo was used to explain learning material, clarify complex topics, ask guiding questions and support students in solving academic tasks independently. Wysa and Woebot Health were used for emotional check-ins, short self-regulation exercises and reflective dialogues related to anxiety, fatigue and loss of concentration. The control group continued studying without these digital support tools. This organisation of the intervention made it possible to compare subsequent changes in academic stress, academic anxiety and emotional exhaustion between students who used AI-based support and students who followed the usual learning process. Before comparing the indicators of the experimental and control groups, it was useful to compare the proportion of students with different levels of academic stress. This presentation made it possible to assess the homogeneity of the groups in terms of the distribution of participants with low, medium and high levels of academic stress even before the use of AI tutors and emotional support systems began (Fig. 1).

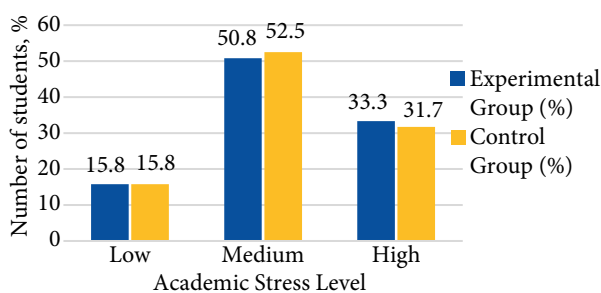


Figure 1. Comparison of initial levels of academic stress in the experimental and control groups

Note: the data were presented as a percentage of the total number of participants in each group ($n = 120$). The proportion of students with low, medium and high levels of academic stress was calculated separately for the experimental and control groups prior to the introduction of AI tutors. No statistically significant differences were found between the groups ($p > 0.05$)

Source: compiled by the author

The distribution of participants by year of study, degree programme and university showed no statistically significant differences between the experimental and control groups. The results of Fisher's exact test for the main categorical indicators did not reach the established significance level. This confirmed that the groups were comparable at the start of the experiment. Initial measurements also showed that academic stress was common among a significant proportion of students. Moderate and high levels of academic stress predominated in the sample, while low stress was recorded in a smaller proportion of participants. Baseline indicators of academic anxiety and emotional exhaustion also remained at a level that allowed further assessment of changes during the intervention. Thus, the results of the initial stage confirmed the balance of the sample and the absence of statistically significant differences between the experimental and control groups before the use of AI-based academic and emotional support tools.

The impact of AI tutors and emotional support systems on students' academic stress

Following the eight-week period of using AI tutors, changes were observed not only in the quantitative indicators of academic stress but also in the nature of the students' study habits. Participants in the experimental group more frequently reported a more organised allocation of study time, fewer instances of leaving tasks until the last few days, and a reduced need to seek additional explanations independently after working through the study material. The results indicated that the use of Khanmigo (n.d.), Wysa (n.d.) and Woebot Health (n.d.) influenced not only the subjective perception of the academic workload but also specific components of learning behaviour that had previously been associated with the onset of academic stress. Eight weeks after the start of using the digital tools, the average level of academic stress in the experimental group fell from 3.69 to 2.81 points ($SD = 0.56$; $p < 0.001$). The changes were fairly uniform across students from different universities and year groups, indicating that the observed effect was not dependent on the specific educational environment. Above all, the aspects of academic activity that had created the greatest burden at the initial stage were the ones that changed. Students reported fewer instances were having to complete several written assignments simultaneously led to a loss of control over the learning process. Some participants noted that, after using Khanmigo, complex topics became easier to work through without having to refer to external information

resources. The explanation of the learning material in a dialogue format allowed misunderstandings of individual concepts to be cleared up more quickly, so re-reading the same sections became less common. There were also noticeable changes in how study time was planned. Whilst at the start of the study a significant proportion of students completed tasks without a clear time allocation, after the experiment concluded, participants more frequently reported using short study sessions, regularly checking their progress, and tackling large projects in stages. This helped to reduce the workload in the run-up to deadlines (Fig. 2).

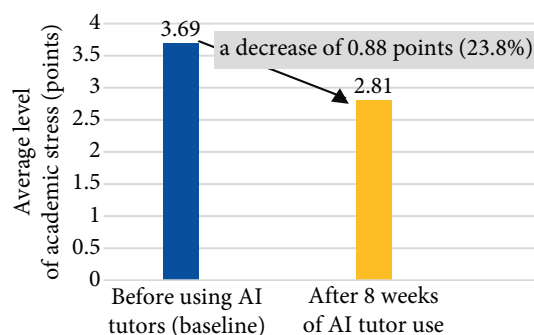


Figure 2. Change in the average level of academic stress in the experimental group before and after using AI tutors

Note: the diagram shows the mean academic stress scores of students in the experimental group before the start of AI tutor use ($M = 3.69$; $SD = 0.60$) and after eight weeks of use ($M = 2.81$; $SD = 0.56$). The reduction in the mean score was 0.88 points (23.8%). A statistically significant difference between the measurements was confirmed by Student's t-test for paired samples ($p < 0.001$)

Source: compiled by the author

Individual responses from students showed that Khanmigo was used primarily as a support tool whilst carrying out specific learning activities. Students entered a section of a problem, asked for an explanation of the sequence of steps to solve it, clarified the meanings of individual concepts from the lecture material, and checked whether had constructed their own line of reasoning correctly. In some cases, the tutor was used to break down a large task into shorter stages: identifying the first step, drawing up a plan for the answer, checking an interim result and formulating a final conclusion. Such actions reduced the number of repeated attempts at the same task, as students received explanations the moment, encountered difficulties. Most often, this related to preparation for tests, written assignments and group projects, where it was necessary to quickly understand the requirements, clarify the logic of the answer or check the sequence of reasoning. The results showed that it was not the automation of learning itself that contributed to a reduction in academic stress, but rather the availability of personalised explanations and the opportunity to receive feedback whilst carrying out learning tasks. The interpretation of these results was

further supported by A. Mehrad *et al.* (2025), who had examined educational stress and the use of artificial intelligence tools among international students in Spanish higher education. Their findings had shown that AI tools could function not only as academic resources, but also as means of reducing uncertainty, language-related difficulties and adaptation problems within an unfamiliar institutional environment. This position was relevant to the study, since the decrease in academic stress was connected not only with lower workload pressure, but also with students' greater ability to organise everyday learning practices. This interpretation was also consistent with the approach proposed by R. Sajja *et al.* (2024), who had developed an artificial intelligence-enabled assistant for personalised and adaptive learning in higher education. Their model had combined accessible explanations, knowledge assessment, personalised learning pathways, quizzes and flashcards as means of reducing cognitive load. A similar mechanism was observed in the study: Khanmigo helped students clarify complex concepts, check the logic of their reasoning and divide larger tasks into shorter stages. Therefore, the reduction in academic stress was associated not with the automation of learning, but with the availability of adaptive support at the moment when students encountered difficulty. Comparable conclusions had been reached by F.A. Flores Limo *et al.* (2023), who had examined ChatGPT as a virtual tutor for personalised learning experiences, and by G. Sornavalli *et al.* (2025), who had considered artificial intelligence as a tool for adapting learning support to students' pace, difficulties and individual educational needs. In the study, this function was reflected in students' use of Khanmigo for explanations, task sequencing and feedback during independent work. These forms of support helped maintain control over the learning process, especially when several assignments or assessments had to be managed simultaneously. The behavioural dimension of these changes corresponded to the case study by A. Baillifard *et al.* (2025), in which effective learning with a personal AI tutor had been analysed through the interaction between individualised assistance and students' learning strategies. The authors had shown that personal AI tutoring was linked to timely explanations, active work with tasks and support during the learning process. In the study, this relationship was reflected in the transition from irregular task completion to shorter study sessions, interim progress checks and staged work on larger assignments. Thus, the decrease in academic stress was connected with changes in learning behaviour rather than with the isolated use of digital explanations. Before comparing the results, the average academic stress scores in the experimental and control groups were compared following the conclusion of the experiment. This made it possible to assess whether the use of AI tutors was accompanied by statistically significant changes compared with students who studied without digital emotional support (Table 6).

Table 6. Comparison of academic stress indicators in the experimental and control groups after the experiment had concluded

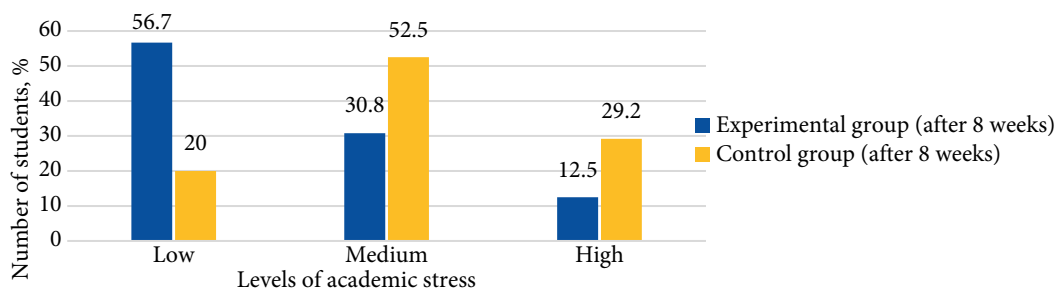
Indicator	Experimental group (N = 120)	Control group (N = 120)	Statistical test	p-value
Mean academic stress score, M (SD)	2.81 (0.56)	3.57 (0.60)	U = 4638	≤0.001
Students with low stress, n (%)	68 (56.7)	24 (20.0)	Fisher's exact test	≤0.001
Students with moderate stress, n (%)	37 (30.8)	61 (50.8)	Fisher's exact test	≤0.001
Students with high stress, n (%)	15 (12.5)	35 (29.2)	Fisher's exact test	0.002

Note: M = mean; SD = standard deviation. Academic stress was assessed using a five-point Likert scale. Differences between groups were evaluated using the Mann-Whitney U test for continuous variables and Fisher's exact test for categorical variables. Statistical significance was established at $\alpha = 0.05$

Source: compiled by the author

The results showed that, after eight weeks of using AI tutors, the experimental group was characterised by a lower average level of academic stress and a higher proportion of students with low levels of academic stress compared to the control group. At the same time, the number of participants with high levels of academic stress in the experimental group decreased significantly. The observed differences between the experimental and control groups were consistent with the conclusions of X. Zhang *et al.* (2025), who had examined the effectiveness of AI-powered tutoring systems in improving learning outcomes. The study had shown that personalised instruction, timely feedback and adaptation to students' needs could support academic progress. In the research, these mechanisms were reflected not only in the organisation of learning activities, but also in lower stress indicators among students who regularly used AI tutors. This suggested that the effect of AI tutoring was not limited to academic performance, since it also helped stabilise study behaviour, reduce uncertainty and ease deadline-related

pressure. The experimental nature of these results may also be considered in relation to G. Kestin *et al.* (2025), who had evaluated AI tutoring through a randomised controlled trial in an authentic educational setting. Their study had shown that a research-based AI tutoring design could produce stronger learning outcomes than in-class active learning. Although the study focused on academic stress rather than achievement, both studies demonstrated the value of AI support under conditions close to ordinary higher education practice. In this research, the advantage of the experimental group was expressed through lower stress scores, a higher proportion of students with low stress and fewer reports of deadline-related overload. Upon completion of the experiment, it was appropriate to compare the distribution of students by levels of academic stress in the experimental and control groups. This comparison made it possible to assess how the proportion of participants with low, medium and high levels of academic stress had changed after eight weeks of using AI tutors and emotional support systems (Fig. 3).

**Figure 3.** Comparison of academic stress levels in the experimental and control groups after the experiment concluded

Note: the diagram shows the distribution of students in the experimental (n = 120) and control (n = 120) groups by levels of academic stress following the completion of the eight-week experiment. Levels of academic stress were determined according to three categories based on the total score on the Likert scale: low (1.00-2.33 points), medium (2.34-3.66 points) and high (3.67-5.00 points). Differences between the groups were statistically significant according to Fisher's test ($p < 0.05$)

Source: compiled by the author

Differences were also evident in the way learning tasks were carried out. Students in the control group reported significantly more often that had a backlog of unfinished work, that had to work in the evenings before deadlines, and that had difficulty concentrating whilst preparing for tests. Participants in the experimental group, by contrast, more often noted that completed tasks gradually, used Khanmigo's recommendations to structure the learning

material, and were less likely to revisit exercises had already completed due to doubts about the correctness of their answers. These changes indicated that the use of the AI tutor primarily influenced the organisation of learning activities, whilst the reduction in academic stress was a consequence of more effective management of the learning process. Before comparing individual psychological indicators, account was taken not only of changes in academic

stress but also of the states that accompanied the study load throughout the experiment. Academic anxiety, emotional exhaustion and satisfaction with the learning process made

it possible to determine whether the use of AI support had an impact on the students' broader experience whilst completing academic tasks (Table 7).

Table 7. Changes in academic anxiety, emotional exhaustion and satisfaction with the learning process

Indicator	Before AI support M (SD)	After AI support M (SD)	Change	p-value
Academic anxiety	3.60 (0.57)	2.74 (0.53)	-0.86	<0.001
Emotional exhaustion	3.22 (0.55)	2.51 (0.50)	-0.71	<0.001

Note: the values were presented as mean scores and standard deviations on a five-point Likert scale. A negative change indicates a decrease in the indicator following the use of AI support. The statistical significance of the differences between the two measurements was tested using Student's t-test for paired samples; the significance level was set at $\alpha = 0.05$

Source: compiled by the author

After the completion of the experiment, students in the experimental group additionally completed the AI Support Satisfaction Questionnaire. The mean satisfaction score was 4.09 (SD = 0.58), indicating a positive evaluation of the accessibility of explanations, the pace of learning, emotional check-ins and self-regulation tools. After eight weeks of using AI support, the reduction in academic anxiety was accompanied by a lower frequency of reports of uncertainty before tests, rechecking of tasks already completed, and difficulties in starting independent work. A similar mechanism was described in a study by Q. Zafar *et al.* (2026), where the use of AI tools was examined in terms of its impact on students' emotional regulation and learning anxiety. The authors found that more active use of AI support was associated with higher levels of emotional regulation and lower levels of learning anxiety. A key point for comparison with the findings was that the reduction in anxiety was attributed not only to access to learning information, but also to the opportunity to receive support whilst performing complex academic tasks. In this study, this relationship manifested itself through reduced uncertainty prior to tests, a reduced need to repeatedly check tasks already completed, and more frequent use of brief self-regulatory actions. At the same time, this study specified the impact of AI support through the combination of Khanmigo's educational tutoring with Wysa's emotional check-ins and Woebot Health's reflective dialogues.

Reduced emotional exhaustion indicated a better distribution of workload throughout the week, whilst increased satisfaction with the learning process reflected a more positive perception of the accessibility of explanations, the pace of learning and digital support. Students' responses indicated that reduced anxiety was accompanied by a change in daily study habits. Participants reported less frequently needing to check completed tasks multiple times, felt less anxious before tests, and were less likely to delay starting work due to uncertainty about their own knowledge. A distinct effect was linked to the use of Wysa and Woebot Health as tools for short-term emotional self-regulation. A similar correlation between emotional support and learning activities was also observed in the study by Y. Zong & L. Yang (2025). The authors considered artificial intelligence as a component of social-emotional learning and demonstrated that taking students' emotional

reactions into account whilst interacted with digital systems was accompanied by an increase in their engagement with the learning process and an improvement in their emotional well-being. The results obtained in this study complemented the findings cited above. A reduction in academic stress was associated with the regular use of brief emotional check-ins and reflective dialogues, which helped students to identify signs of burnout in a timely manner, adjust their study routine and regain concentration more quickly. Unlike the study by Y. Zong & L. Yang, the main focus was not on changes in academic engagement, but on the dynamics of academic stress, academic anxiety and emotional exhaustion.

Throughout the academic day, students carried out emotional check-ins: indicated their current state, selected options such as tension, fatigue, anxiety or loss of concentration, and then received brief recommendations. Most often, these recommendations involved taking a 5-10-minute break, doing a breathing exercise, breaking the task down into smaller parts, returning to a specific step, or noting the cause of the tension in a short text message. In their responses, students described these interactions as a way to halt the build-up of fatigue more quickly whilst working independently. Some participants noted that after checking in, did not stop studying altogether, but changed their approach: took a short break, returned to a simpler part of the task, clarified the next step in Khanmigo, or postponed part of the work to another time slot. This reduced the number of instances where fatigue led to the task being put aside entirely. The satisfaction score for the learning process also changed. Whilst the average score at the start of the study was 3.18, it rose to 4.09 by the end of the experiment. Most often, students attributed the positive changes to the speed at which explanations were provided, the ability to work at their own pace, concise self-regulation tools, and the fact that did not need to wait for a lecturer's consultation to resolve specific learning difficulties. This position was consistent with the findings of A. Gurung *et al.* (2025), who had shown that human tutoring could strengthen the learning effect of AI tutor use. Their study had demonstrated that the impact of AI-supported learning depended not only on the technological quality of the tutor but also on the presence of pedagogical guidance that helped students interpret feedback and

apply it productively. In the study, this idea was reflected in students' perception of AI tools as supplementary instruments for independent work between classroom sessions. Therefore, the reduction in academic stress should be interpreted as the result of combined digital and pedagogical support, rather than as an argument for replacing lecturer involvement. At the same time, the majority of participants did not view AI as a complete replacement for a lecturer. The prevailing view in the responses was that digital systems were most useful during independent study between classroom sessions and when completing homework assignments. This stance taken by the students highlighted the issue of the balanced use of AI in higher education, as discussed by B. Klimova & M. Pikhart (2025). Author's review demonstrated that artificial intelligence can support personalised learning, psychological support and the effectiveness of educational communication; however, its

excessive use was associated with risks of digital fatigue, technostress, social isolation and a reduction in face-to-face interaction between participants in the educational process. In this study, such risks were partially mitigated by the very design of the experiment: Khanmigo, Wysa and Woebot Health were used as supplementary tools between classroom sessions, rather than as a substitute for teaching support. The results showed that the positive effect of AI support was linked to its measured use for independent work, emotional check-ins and brief reflective activities, rather than to the transfer of all educational interaction to a digital environment. To verify the validity of the identified changes, a comprehensive statistical analysis was carried out, which made it possible to assess both the differences between repeated measurements and the results of the comparison between the experimental and control groups after the use of AI tutors had ended (Table 8).

Table 8. Results of the statistical analysis of the effectiveness of AI tutors

Indicator	Statistical test	Test value	P-value	Effect size	Interpretation
Academic stress	Paired samples t-test	t = 12.84	<0.001	Cohen's d = 0.91	Large effect
Academic anxiety	Paired samples t-test	t = 11.63	<0.001	Cohen's d = 0.84	Large effect
Emotional exhaustion	Paired samples t-test	t = 9.94	<0.001	Cohen's d = 0.73	Medium to large effect
Academic stress distribution	Fisher's exact test	χ^2 equivalent = 14.27	<0.001	Cramer's V = 0.31	Moderate association
Post-intervention group comparison	Mann-Whitney U test	U = 4638	<0.001	r = 0.42	Moderate effect
Non-normal indicators	Wilcoxon signed-rank test	Z = -7.86	<0.001	r = 0.51	Large effect

Note: the paired t-test was used to compare the experimental group's indicators before and after the use of AI tutors. The Wilcoxon test was used for indicators whose distribution did not follow a normal distribution. The Mann-Whitney U test was used to compare the experimental and control groups after the experiment had concluded, whilst Fisher's exact test was used to compare the proportions of students with different levels of academic stress. The level of statistical significance was set at $\alpha = 0.05$

Source: compiled by the author

In addition to the comparison of pre- and post-experiment indicators, Pearson's correlation analysis was conducted to determine the relationships between the intensity

of AI tutor use, emotional check-ins, satisfaction with AI support and changes in academic stress, academic anxiety and emotional exhaustion (Table 9).

Table 9. Correlations between AI support use and changes in students' psychological indicators

Variable pair	Pearson's r	P-value	Interpretation
Frequency of AI tutor use and reduction in academic stress	-0.58	<0.001	Moderate negative correlation
Frequency of AI tutor use and reduction in academic anxiety	-0.51	<0.001	Moderate negative correlation
Frequency of emotional check-ins and reduction in emotional exhaustion	-0.47	<0.001	Moderate negative correlation
Satisfaction with AI support and reduction in academic stress	-0.54	<0.001	Moderate negative correlation
Trust in AI recommendations and reduction in academic stress	-0.49	<0.001	Moderate negative correlation
Agreement between algorithmic emotion recognition and self-assessment	0.63	<0.001	Strong positive correlation

Note: Pearson's correlation coefficient was used to assess the relationship between AI support variables and changes in students' psychological indicators. Negative coefficients indicate that more frequent or more positively evaluated use of AI support was associated with lower levels of academic stress, academic anxiety and emotional exhaustion after the experiment. Statistical significance was established at $\alpha = 0.05$

Source: compiled by the author

The correlation analysis showed that more frequent use of AI tutors was associated with lower post-experiment levels of academic stress and academic anxiety. Emotional check-ins were also related to reduced emotional exhaustion. A positive correlation between algorithmic emotion recognition and students' self-assessments confirmed that the digital systems reflected the

students' reported emotional states with sufficient consistency. Alongside testing for statistical significance, identified which characteristics of the learning process were most strongly associated with a reduction in academic stress. To this end, the results were summarised using a regression model, which enabled to assess the contribution of each predictor (Fig. 4).

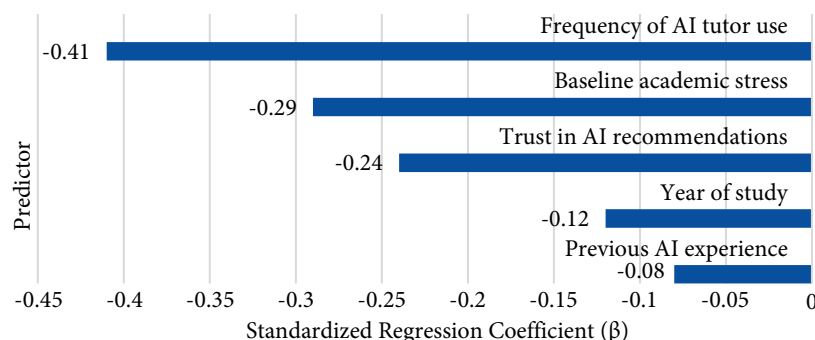


Figure 4. Contribution of individual factors to the reduction in academic stress based on the results of regression analysis

Note: the diagram shows the standardised regression coefficients (β) obtained from the results of multiple regression analysis. Higher absolute values of β indicate a stronger contribution of the corresponding predictor to the reduction in academic stress

Source: compiled by the author

Calculation of the effect size showed that the changes in academic stress corresponded to a large effect (Cohen's $d = 0.91$), whilst values of 0.84 and 0.73 were obtained for academic anxiety and emotional exhaustion, respectively. This indicated that the observed changes were not only statistically significant but also had practical implications for the organisation of university support for students. The results showed that combining Khanmigo's academic support with the emotional support systems Wysa and Woebot Health helped to reduce academic stress, improve self-regulation of learning activities and increase satisfaction with the educational process. The most significant changes were observed in the organisation of independent study, the planning of study time and the reduction of stress associated with challenging academic tasks, indicating that the use of AI-based support tools was accompanied by improvements in several aspects of students' academic self-management.

The effectiveness of mood recognition algorithms and AI-supported student support functions

Once changes in academic stress levels had been established, it became necessary to assess how effectively the emotion recognition algorithms reflected students' actual experiences and how individual AI support functions were linked to changes in psychological indicators. The results obtained made it possible to compare the algorithmic determination of emotions with the participants' self-assessments, to trace the relationship between the intensity of digital tutor use and the dynamics of academic stress, and to identify the features that students considered most useful when completing academic tasks. A comparison of the

results of automatic emotional state recognition with students' self-assessments revealed a fairly high level of agreement between them. A similar approach was presented in the work of S. Javed *et al.* (2025), where the recognition of students' emotional signals was considered a prerequisite for personalised support in a virtual learning environment. The authors demonstrated that more accurate identification of emotional reactions was associated with enhanced social-emotional learning and individualised academic support. In their study, emotional signals were treated not as a secondary parameter of digital interaction, but as information enabling timely adjustments to the nature of learning support. This was consistent with the findings presented here, where algorithmic identification of states of calm, tension, fatigue and anxiety was used to select brief recommendations in Wysa and Woebot Health. The difference lay in the fact that, in this study, the accuracy of emotion recognition was verified by comparing it with students' self-assessments, whilst the subsequent interpretation was linked to changes in academic stress.

In most cases, the Wysa and Woebot Health algorithms correctly identified the general nature of the emotional state that students reported during brief check-ins. The highest agreement was observed for assessments of tension, fatigue, motivation and calmness. Lower agreement was observed for feelings of uncertainty and anxiety, as some students described these as interrelated experiences. Before presenting the summarised results, individual emotional states recorded during check-ins in Wysa and Woebot Health were compared. This made it possible to determine for which states algorithmic recognition most accurately corresponded to the students' self-assessments (Table 10).

Table 10. Agreement between algorithmic recognition of emotional states and students' self-assessments

Emotional state	Agreement with student self-assessment (%)	Interpretation
Calmness	92.5	Very high agreement
Tension	89.2	High agreement
Fatigue	87.4	High agreement
Motivation	84.8	High agreement
Anxiety	82.1	Moderate to high agreement

Table 10. Continued

Emotional state	Agreement with student self-assessment (%)	Interpretation
Uncertainty	79.7	Moderate agreement
Mean agreement	86.3	High overall agreement

Note: the percentage of agreement reflects the proportion of cases in which the algorithmic determination of emotional state coincided with the student's self-assessment during a brief emotional check-in. The data were aggregated from the results of students' interactions with Wysa and Woebot Health over the eight-week duration of the experiment

Source: compiled by the author

Individual student responses corroborated the quantitative results. Before starting challenging written assignments, participants often described their state as "tension" or "uncertainty". After completing the brief check-in, the system recommended taking a short break, outlining the first stage of the task, or starting with the simplest part. Following this, the majority of students reassessed their state as less tense, which corresponded to the changes simultaneously recorded by the algorithm. A noticeable difference remained between short-term academic anxiety and persistent emotional exhaustion. Whilst the system identified brief emotional reactions with reasonable accuracy, signs of accumulated fatigue more often required several consecutive check-ins. In such cases, the algorithm took into account the repetition of responses and gradually adjusted the content of its recommendations, suggesting not only breathing exercises but also adjustments to the study routine, planning of breaks or a review of the sequence of tasks. The results showed that the algorithms used were suitable for providing pedagogical support to students, as enabled changes in emotional state to be identified in a timely manner without the need for constant intervention by a teacher or psychologist. Verifying the accuracy of recognition provided a basis for assessing whether the intensity of use of digital tutors was linked to changes in academic stress.

The results showed that the intensity of use of AI tutors was directly linked to a reduction in academic stress. Students who worked regularly with Khanmigo, Wysa and Woebot Health throughout the experiment demonstrated a more pronounced improvement compared with participants who used digital support only occasionally. For further analysis, the experimental group was provisionally divided into three categories based on the average number of interactions with the systems per week. The first category comprised students who used the AI no more than twice a week; the second, between three and five times; and the third, more than five interactions per week. The greatest reduction in academic stress was recorded among students in the third category. On average, their score fell by 1.07 points. In the second category, the reduction was 0.83 points, whilst among participants with the lowest frequency of use of digital tutors, the change did not

exceed 0.39 points. A similar pattern was observed with regard to academic anxiety. Regular use of the system was accompanied by fewer reports of difficulties in starting tasks, fear of making mistakes, and double-checking answers that had already been prepared. Students more often reported that began work immediately after receiving an assignment, rather than putting it off until the last few days. The nature of interaction with the various digital tools also differed. Khanmigo was most frequently used to explain specific concepts, check the logic behind problem-solving, and structure written assignments. Wysa was used mainly after several hours of continuous study or before beginning exam preparation, when students reported feeling tired or having difficulty concentrating. Woebot Health was used for short reflective dialogues that helped students assess their own emotional state and identify the causes of stress. The frequency of use varied depending on the stage of the semester.

This dynamic corresponded to the position developed by H.E. Sari *et al.* (2024), who had examined the improvement of educational outcomes through adaptive learning systems using artificial intelligence. In their study, adaptive learning had been associated with the ability of digital systems to modify content, feedback and learning pathways according to students' progress and current educational needs. This perspective was relevant to the findings because the frequency and purpose of using Khanmigo, Wysa and Woebot Health changed as the semester progressed. During the final weeks, AI support was used more intensively for explanations, answer checking and emotional check-ins, which indicated that adaptive digital support became more significant when academic pressure increased. The increase in the number of enquiries to AI tools reflected changes in students' learning needs over the course of the semester. In the early weeks, digital tutors were used primarily to help students adapt to the format of the course and to clarify specific aspects of the material. As the final assessment approached, interactions became more regular: Khanmigo was used more frequently to explain the material and check the logic of answers, whilst Wysa and Woebot were used for brief emotional check-ins following longer study sessions (Table 11).

Table 11. Frequency of use of AI tutors depending on the stage of the academic semester

Stage of the semester	Khanmigo interactions m (sd)	Wysa check-ins m (sd)	Woebot Health sessions m (sd)	Total AI interactions m (sd)
Weeks 1-2	2.4 (0.8)	1.6 (0.7)	1.2 (0.6)	5.2 (1.4)
Weeks 3-4	3.1 (0.9)	2.0 (0.8)	1.5 (0.7)	6.6 (1.6)

Table 11. Continued

Stage of the semester	Khanmigo interactions m (sd)	Wysa check-ins m (sd)	Woebot Health sessions m (sd)	Total AI interactions m (sd)
Weeks 5-6	3.8 (1.0)	2.4 (0.9)	1.8 (0.8)	8.0 (1.8)
Weeks 7-8	4.6 (1.1)	3.0 (1.0)	2.1 (0.8)	9.7 (2.0)

Note: values were presented as the average number of interactions per student with the respective AI tool over the course of a week. M = mean; SD = standard deviation. The increase in the frequency of interactions during weeks 7-8 coincided with the period of preparation for the final assessment

Source: compiled by the author

The students' responses regarding the nature of their use of the systems were also revealing. A significant proportion of participants reported that had gradually stopped turning to AI only when difficulties arose. Instead, digital tutors began to be used as a tool for advance planning of their studies: to draw up a brief study plan, check progress, or assess their readiness for a test. This change in behaviour was accompanied by a more even distribution of the study load throughout the week and fewer instances of several major tasks being completed simultaneously in the run-up to deadlines. The findings can be interpreted in relation to M.P. Pratama *et al.* (2023), who had considered artificial intelligence as a means of organising personalised learning through the adaptation of educational content to students' individual needs. Their study had shown that AI-based learning environments could increase engagement and improve learning outcomes by moving away from uniform instructional models. In the study, this position was specified through changes in students' learning behaviour: digital tutors were used not only to obtain explanations, but also for planning, progress checking and preparation for assessment. A similar issue had been addressed by H.H. Ariza (2026a), who had examined AI-powered tutoring systems capable of providing personalised guidance and assessment. Adaptive

tutoring in that study had been linked to the adjustment of instructional support to students' progress, difficulties and learning patterns. This corresponded to the findings, where Khanmigo's value was manifested in the alignment of guidance, task sequencing and feedback with the specific difficulties students encountered while preparing assignments and assessments. The benefits and limitations of this approach had been examined by W. Shoukat *et al.* (2025), who had considered AI tutors as instruments for personalised learning. Their analysis had shown that such tools could support individual learning trajectories, provide timely feedback and increase access to academic assistance, while also raising issues of technological dependence, data privacy and teacher supervision. This perspective was important for interpreting the results, since the reduction in academic stress was associated with the supplementary use of Khanmigo, Wysa and Woebot Health within independent study, rather than with the displacement of pedagogical interaction. Student evaluations showed that the AI support functions of greatest practical value were those linked to a specific learning activity: explaining the material, breaking a task down into stages, or quickly regaining concentration. General support functions received lower ratings, as did not always correspond to the student's current learning situation (Table 12).

Table 12. Students' evaluation of AI support functions following the completion of the experiment

AI support function	AI tool	Mean score (m)	Main use reported by students	Interpretation
Explanation of learning material	Khanmigo	4.61	Clarifying concepts, checking task logic, verifying written answers	Most valued function because it directly supported task completion
Step-by-step task guidance	Khanmigo	4.48	Dividing essays, coursework, presentations, and complex tasks into smaller stages	Helped students start work and reduce uncertainty about task sequence
Emotional check-ins	Wysa	4.36	Recording current emotional state, receiving short recommendations for breaks and concentration	Supported emotional self-regulation during intensive learning periods
Reflective dialogues	Woebot Health	4.29	Structuring emotional reactions after long study sessions or before assessment	Helped students identify causes of tension and prevent emotional overload
Automatic motivational messages	Khanmigo/Wysa/Woebot Health	3.71	Receiving short general encouragement during learning sessions	Less valued because generic messages were perceived as less useful than personalised recommendations

Note: ratings were made on a five-point Likert scale, where 1 indicated the minimum usefulness of a function and 5 the maximum. The data reflect the responses of students in the experimental group after eight weeks of using AI tutors and emotional support systems

Source: compiled by the author

The results also revealed differences depending on the year of study. First- and second-year students made more frequent use of the functions for explaining course material

and checking the correctness of answers. For students in higher years, tools for planning work, monitoring the progress of major projects and organising time were in greater

demand. In the final survey, 88.3% of students in the experimental group reported that were willing to continue using similar digital tools. At the same time, only 6.7% of participants noted that the use of AI had virtually no impact on how organised their studies, whilst 5.0% were undecided in their assessment. A qualitative analysis of the responses showed that the positive perception of digital tutors was not solely linked to the speed at which answers were received. Students repeatedly noted that the ability to ask a follow-up question, clarify an unclear point or have an explanation repeated without feeling any psychological discomfort contributed to greater confidence when working independently. Some participants reported that, after several weeks of using AI, turned to digital assistants less frequently with simple questions, as gradually developed their own strategies for planning their study activities. The positive perception of specific AI support functions provided a basis for identifying the factors most closely associated with reduced academic stress. This interpretation was consistent with the findings of R. Suriá-Martínez *et al.* (2025), who had examined emotional profiles and their relationship with artificial intelligence use among university students. Their study had shown that students' interaction with AI tools was related to differences in emotional characteristics and patterns of digital engagement. In the research, this perspective helped explain why emotional check-ins and reflective dialogues were among the most highly rated functions. These tools supported the recognition of tension, fatigue and uncertainty during independent study, which contributed to more deliberate regulation of learning behaviour. The functional dimension of personalised AI tutoring had also been examined by A.I. Jony *et al.* (2025), who had identified personalised feedback, adaptive guidance, progress monitoring and responses to immediate learning needs as key features of AI tutoring systems in higher education. This approach specified the results presented in Table 11. Students gave the highest ratings not to general motivational messages, but to functions directly connected with academic activity: explanation of material, step-by-step task guidance, emotional check-ins and reflective support. Therefore, the effectiveness of AI tutoring was associated with targeted support integrated into the learning process, rather than with the mere presence of digital interaction.

A regression model revealed that the reduction in academic stress was primarily linked to behavioural characteristics of AI support usage. The most noticeable changes were observed when students turned to digital tutors regularly, rather than only in situations of acute academic pressure. In such cases, Khanmigo was used for advance planning, checking the logic of task completion and preparing for assessments, whilst Wysa and Woebot Health supported short cycles of emotional self-regulation throughout the academic week. The initial level of academic stress remained a key factor. Students with higher baseline levels had greater scope for positive change, as were the ones most likely to report difficulties with concentration, procrastination and an uneven distribution of their academic workload. After

eight weeks of working with the AI tools, this group more frequently demonstrated a shift from reacting to deadlines on a case-by-case basis to more consistent planning of their study activities. The influence of trust in digital recommendations was particularly evident. Students who not only received advice from the system but also applied it in their study practice were more likely to report a more consistent pace of work, timely breaks and fewer instances of a significant backlog of tasks accumulating before the deadline. The course of study and previous experience of using AI were also significant, but their contribution was weaker compared to the regularity of interaction and the acceptance of personalised recommendations.

The model's results showed that the effectiveness of AI support was determined not by the mere fact of using digital services, but by the regularity of interaction with the system and the students' willingness to apply the recommendations received to their own learning activities. The greatest improvements were observed among participants who combined the use of Khanmigo for solving academic tasks with regular emotional check-ins on Wysa and short reflective sessions on Woebot Health. The results also helped to explain the differences between individual students who had similar initial levels of academic stress. With the same level of academic workload, better results were demonstrated by participants who used digital support as part of their day-to-day study routine, rather than merely as a means of responding to difficulties that had already arisen. The findings indicated a relationship between the systematic use of artificial intelligence tutors, emotional support functions and a reduction in academic stress. The greatest contribution was associated with personalised learning recommendations, regular emotional check-ins and self-regulation tools integrated into students' daily study routines. This conclusion may be interpreted through the framework proposed by A. ElMessiry (2025), in which a personalised artificial intelligence educational tutor had been presented as a model for customised student education. The framework had combined machine learning, natural language processing and adaptive learning algorithms to adjust educational content and learning strategies to individual students' needs. In the context of the study, this approach made it possible to clarify why the regular application of recommendations was more important than occasional access to digital tools. The reduction in academic stress was associated with the integration of AI support into students' ordinary learning behaviour, where explanations, planning prompts and self-regulatory actions were adapted to the specific difficulties encountered during independent study.

The results demonstrated a high level of agreement between algorithmic recognition of emotional state and students' self-assessments, confirming the suitability of the algorithms used for pedagogical support of the learning process. More frequent use of Khanmigo, Wysa and Woebot Health was associated with a more pronounced reduction in academic stress, academic anxiety and emotional

exhaustion. Students rated the features providing explanations of learning material, step-by-step recommendations, emotional check-ins and self-regulation tools most highly. Regression analysis confirmed that the greatest influence on the reduction of academic stress was exerted by the regularity of use of digital tutors, the initial level of academic stress and the level of trust in the recommendations of artificial intelligence systems. This made it possible to consider the combination of academic and emotional support as one of the factors enhancing the effectiveness of digital support for students in higher education institutions.

CONCLUSIONS

The study found that the sample had a balanced structure in terms of universities, study programmes, specialisms and distribution between the experimental and control groups. A total of 240 students from three universities in Spain took part in the study. Baseline measurements showed that academic stress was prevalent among a significant proportion of participants: moderate and high levels of academic stress predominated. At the same time, no statistically significant differences were found between the experimental and control groups prior to the use of AI tools, which provided a basis for further comparison of the results. After eight weeks of using Khanmigo, Wysa and Woebot Health, the experimental group showed a reduction in academic stress, study-related anxiety and emotional exhaustion. The average level of academic stress fell from 3.69 to 2.81 points, whilst in the control group it remained close to the initial value. A reduction in the proportion of students experiencing high levels of stress and an increase in satisfaction with the learning process were

also observed. According to the participants' responses, these positive changes were linked to the ability to obtain explanations of the course material more quickly, plan the completion of assignments, check progress, and use brief emotional self-regulation tools.

Mood recognition algorithms demonstrated a sufficient level of correlation with students' self-assessments, particularly when identifying states of calm, tension and fatigue. Regular use of AI support was associated with a more pronounced reduction in academic stress. Students rated the functions for explaining learning material, step-by-step recommendations, emotional check-ins and brief reflective dialogues most highly. Regression analysis showed that the strongest associations with reduced academic stress were the regularity of digital tutor use, the initial level of stress and trust in the recommendations of artificial intelligence systems. The results confirmed the pedagogical value of combining academic and emotional AI support within a university educational setting. Prospects for further research include expanding the sample size, extending the duration of observation, and comparing the effectiveness of different AI tutor models and emotional state recognition algorithms within the context of university education.

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The impact of artificial intelligence and virtual technologies on the education of graphic and landscape designers

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Abstract. The digitalisation of design education has intensified the need for a methodological understanding of the application of artificial intelligence, virtual reality, and augmented reality in the training of graphic and landscape designers. The aim of the study was to determine how digital tools transform the educational and project-based preparation of design students. The research methodology was based on a theoretical and analytical review of scientific publications, professional reports, and industry materials using comparative analysis, systematisation, logical-analytical methods, and theoretical generalisation. The study established that artificial intelligence, virtual reality, and augmented reality perform different functions in designers' education and are integrated into educational and professionally oriented projects in different ways. Analysis of the sources demonstrated that the use of digital technologies changes the logic of the creative process: project work becomes more iterative, relying on the generation, testing, refinement, and justification of solutions. It was found that the role of the lecturer may shift from assessing only the final product to supporting the design process, analysing digital stages of work, and evaluating the student's individual contribution. The analysis showed that the training of designers requires the integration of digital tools with fundamental design practices, including hand sketching, conceptual analysis, and contextual validation of solutions. It was substantiated that methodological regulation of the use of artificial intelligence, virtual reality, and augmented reality is necessary to preserve independent design exploration, transparency of authorship, and ethical responsibility in educational projects. The results of the study may be used by lecturers, curriculum developers, and heads of design courses when updating the content of design education, developing learning tasks, and establishing assessment criteria for digital design projects

Keywords: design education; professional competencies; visualisation; project analytics; option generation; educational programmes

INTRODUCTION

The digital transformation of design education is reshaping the tools, structure, and content of project-based training for future professionals. Artificial intelligence (AI), virtual reality (VR), and augmented reality (AR) are increasingly being incorporated into the processes of idea generation, visualisation, modelling, evaluation, and presentation of design solutions, which is particularly significant for graphic and landscape design. In these fields, students are required not only to master compositional, artistic, and spatial principles, but also to work effectively with digital environments, analyse generated alternatives, justify authorship decisions, and consider the conditions of project implementation. Consequently, there is a need to develop a methodological understanding of how these technologies

can be integrated into the educational process without diminishing the role of independent design exploration, hand sketching, critical analysis, and authorial responsibility. Examining the possibilities and limitations of AI, VR, and AR makes it possible to identify directions for updating educational programmes and aligning designer training with the evolving demands of professional practice.

Research has shown that the digital transformation of design education affects not only the tools used but also the sequence of educational and project activities. The design process is increasingly organised as a cycle of generation, selection, evaluation, refinement, and justification of solutions. In the training of graphic and landscape designers, this necessitates combining digital tools with individual

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analysis, manual development, contextual validation, and documentation of the student's independent contribution. In the study by T.J. Reynolds & A. Batley (2024), generative AI was presented as a tool that expands the initial stage of design exploration and accelerates the development of visual hypotheses. Their findings demonstrated that AI contributes not only to the generation of alternatives but also to the refinement of design directions, comparison of solutions, and iterative development of ideas. The authors concluded that the educational value of AI lies not in the act of generation itself but in the student's ability to select, edit, and integrate the generated materials into their own design methodology. This issue is further explored in the work of Y. Yin *et al.* (2025), which identified the limitations of traditional assessment focused solely on the final design product in contexts involving AI use. Lecturers were not always able to confidently distinguish between assignments completed independently by students and those created with the assistance of generative tools. This suggests the need to evaluate not only the visual completeness of a project but also the process through which it is produced, including functional justification, technical feasibility, ethical considerations, and the degree of the student's individual contribution. With regard to immersive technologies, Z. Lin *et al.* (2023) demonstrated that virtual studios can support collaborative design activities within digital environments. Their findings indicated that group discussions, idea exchange, collaborative object creation, and informal communication among participants could be maintained effectively in virtual settings. Thus, VR performs not only a visualisation function but also an organisational one, enabling project activities to be structured within a digital studio environment. A similar conclusion was presented by F. Castronovo *et al.* (2023), who associated VR-based design reviews with increased learner self-efficacy when evaluating project solutions. Spatial models facilitate the perception of scale, proportions, relationships between elements, and potential design flaws. For design education, this indicates that VR can serve as a tool for evaluating design solutions prior to final presentation or professional review.

In the field of illustration, N. Lewis (2025) demonstrated that generative AI does not eliminate the need for professional manual and editorial work. Generated images may be used during the initial stages of exploring form, colour, lighting, and overall visual atmosphere; however, they require subsequent refinement and stylistic control. This finding confirms the importance of preserving fundamental skills in drawing, compositional analysis, and authorial revision within educational programmes. In his study, R. Heaton (2025) associated the use of AI in art education with issues of pedagogical responsibility, authorship, and ethical reflection. AI is regarded not as an autonomous substitute for artistic practice but as part of an educational dialogue concerning technology, influence, limitations, and the responsibilities of the creator. This highlights the need to introduce guidelines for working with AI-generated content, documenting stages of generation, and

discussing the ethical implications of digital tools within designer training. In the work of Y. Hwang & Y. Wu (2025), generative image models were associated with changes in the role of the graphic design student. The student acts not merely as a producer of visual form but also as an organiser of content, context, semantic structure, and visual interpretation. These findings indicate that graphic design education is shifting from the mastery of individual techniques towards the development of the ability to manage digital visual content and justify its communicative function. W. Gao *et al.* (2025) linked the integration of generative AI into product design education with changes in learning tasks and professional competencies. AI is incorporated into idea generation, development of alternatives, prototyping, evaluation of options, and refinement of design outcomes. Consequently, the integration of AI requires reconsideration of assessment criteria, since the significance lies not only in the final product but also in the logic of interaction with generative systems, the quality of selection, and the degree of authorial refinement applied to the material.

Thus, recent studies indicate a broader shift in design education: digital technologies are transforming not only methods of visualisation but also the organisation of the design process itself. Generative AI expands the range of conceptual alternatives while simultaneously requiring transparency of authorship, preservation of manual and analytical skills, and the development of new assessment criteria. Immersive environments enhance spatial evaluation, collaborative design, and educational communication, reinforcing the need for methodological regulation of AI and VR applications in the training of graphic and landscape designers. In the studies reviewed, AI, VR, and AR are most often examined separately, without a comprehensive analysis of their combined functions in the education of graphic and landscape designers. The aim of the study was to identify the impact of modern digital tools on the content, structure and methodology of students' educational and project-based training in the field of design. The research objectives were: to systematise the areas of application of generative and immersive digital tools in the educational and project-based training of graphic and landscape designers; to identify the professional competences developed through the use of digital technologies, as well as the risks associated with their integration and methods of pedagogical regulation.

MATERIALS AND METHODS

For this theoretical-analytical study, the research design incorporated source analysis, systematisation, comparative analysis, logical-analytical methods, and theoretical generalisation of scientific publications, professional reports, and industry materials addressing the application of AI, VR, and AR in design education and project practice. Source analysis was employed to identify and evaluate publications examining the use of digital technologies in the training of graphic and landscape designers. The review primarily included English-language sources published

between 2023 and 2026 and retrieved from the websites of professional organisations, and Google Scholar (n.d.), ScienceDirect (n.d.), MDPI (n.d.), SAGE Journals (n.d.), Frontiers (n.d.), EDUCAUSE Review (n.d.). Searches were conducted using the keywords generative AI in design education, virtual reality in design education, augmented reality in graphic design, AI in landscape architecture, and immersive technologies in higher education. The selection included peer-reviewed articles, conference proceedings, review papers, professional reports, and analytical documents addressing educational, project-related, professional, and ethical aspects of AI, VR, and AR implementation. Promotional materials, duplicate publications, and sources mentioning digital technologies without analysing their functions in education or project practice were excluded.

The systematisation method was used to group sources by technological areas and analytical categories. The materials were categorised as follows: AI, VR and AR functions; educational applications; professionally oriented use; competencies developed; risks of integration; pedagogical regulation. This categorisation made it possible to distinguish materials on generative tools from research devoted to virtual and augmented environments, as well as to compare their educational and project-based functions.

A comparative method was used to contrast AI, VR and AR across several analytical categories: the functions of the technologies, educational applications, professionally oriented use, competencies developed, risks of integration and pedagogical regulation. The functions of digital technologies in design education were examined based on the works of A.M. Al-Ansi *et al.* (2023), O. McGrath *et al.* (2023) and S.Y. Andalib & M. Monsur (2024). Meanwhile, the educational applications of generative and immersive tools were analysed based on publications by N. Hu (2024), J. Ha *et al.* (2024) and S. Habib *et al.* (2024). The professionally oriented use of digital tools in graphic and landscape design was clarified with reference to materials from the Landscape Architecture Foundation (2023), American Society of Landscape Architects (2025) and International Federation of Landscape Architects (2025).

The competencies being developed in designers were summarised on the basis of research by N. Wang *et al.* (2025), S. Zhou *et al.* (2025) and K. Fleischmann (2026). This summary, further informed by the work of S. Alkhateeb *et al.* (2026), includes working with generative systems, formulating queries, the critical selection of digital outputs, design analytics, immersive modelling, authorial control, ethical literacy and interdisciplinary design. The risks associated with the integration of digital tools, including issues of authorship, ethics, legal restrictions, physiological strain and digital inequality, were examined in the works of A. Skulmowski (2023), S. Altaf (2024) and M.G. Wagner (2025). Additionally, these challenges were analysed in light of the research by V. Strunk & J. Willis (2025), which explores issues of learner autonomy and the mindful use of generative tools.

The pedagogical regulation of the use of AI, VR and AR was analysed with reference to the works of L. Eaves & J. Adair (2026) and the Digital Education Council (2026). Materials from the Canadian Society of Landscape Architects (n.d.), the World Economic Forum (2025) and the Organisation for Economic Co-operation and Development (2026) were used to compare professional requirements, the risks of automation and directions for updating educational programmes, as well as to analyse changes in professional competences, requirements for specialist training and the organisational and technological conditions for the implementation of AI in educational and design environments, including the interaction between humans and generative systems during the design process. A logical-analytical method was employed to identify links between digital technologies, design practice, professional requirements and the updating of educational programmes, including an assessment of the transformation of design functions, the risks of standardisation of visual language and changes to the professional role of the designer.

The method of theoretical generalisation was applied to formulate pedagogical conditions for regulating the use of digital tools in design education. Based on a synthesis of the sources, the following conditions were identified: preliminary analysis of the design brief; recording of requests to AI; documentation of the stages of generation and refinement; preservation of manual sketching; development of AI literacy; critical review of digital outputs; and the introduction of rules for the ethical use of digital content. The research methodology ensured a comprehensive examination of the issue through a combination of source analysis, systematisation, the comparative method, the logical-analytical method and theoretical generalisation. A limitation of the study lies in its theoretical-analytical nature, as the research did not involve any pedagogical experiments, student questionnaires, interviews with lecturers or observation of the actual application of AI, VR and AR in the teaching process.

RESULTS AND DISCUSSION

The integration of AI, VR and AR into the educational process has the potential to transform the training of students and young professionals in the fields of graphic and landscape design. These technologies can accelerate the mastery of specific design operations, broaden the scope of creative exploration, and enable a swifter transition from the initial idea to the analysis, comparison and refinement of design solutions (Al-Ansi *et al.*, 2023; Habib *et al.*, 2024). In the traditional teaching model, the stages of idea generation, sketching, stylistic selection, composition development and preliminary visualisation are usually carried out sequentially. Generative AI changes this logic: even at the initial stage, a student can obtain several visual hypotheses, compare them with one another and select a direction for subsequent creative refinement. Thus, the educational value of AI lies not only in accelerating the creation of options, but also in shifting the focus to their critical analysis, the

justification of choices and the assessment of their suitability for the design brief.

In graphic design, AI is used in the development of posters, corporate identity, packaging, advertising layouts, interface solutions and visual concepts for communication campaigns. Tools such as Midjourney, DALL-E, Stable Diffusion and specialised design platforms such as Canva Magic Design, Figma AI and Runway enable the creation of initial images, style references, compositional schemes, colour schemes and variations in the text-to-image ratio. The use of generative AI can accelerate the creative process by 30-50% and enhance the efficiency of design work (Ee & Tasir, 2026). At the same time, AI broadens the range of possibilities in the design exploration process. Students are given the opportunity to work not with a single sketch, but with a series of alternative solutions that differ in composition, style, visual metaphor, colour, scale, rhythm and visual hierarchy. In this context, AI functions as a tool for divergent thinking, as it facilitates the rapid generation of various compositional, stylistic and conceptual options. However, the quality of a creative solution is determined not by the mere use of AI, but by the extent to which the final result corresponds to the design brief, the target audience, the functional purpose and the visual logic of the project.

In landscape design, the use of AI is linked to the development of site layout options, the search for a conceptual vision, the comparison of functional zoning scenarios and the preparation of preliminary visualisations. Its significance is particularly evident in projects where a combination of spatial, environmental and user-related parameters must be taken into account: topography, landscaping, vantage points, climatic conditions, the social function of the space and the nature of users' behaviour. In this context, AI enables the site to be viewed not only as a visual object, but also as a system of natural, social and infrastructural interrelationships. The application of AI in landscape architecture involves processing large datasets, analysing complex ecosystems and developing variant design approaches (Landscape Architecture Foundation, 2023). VR and AR complement the capabilities of AI by enabling a shift from a two-dimensional representation of a project to a three-dimensional and interactive model. In the training of graphic and landscape designers, these technologies develop skills in 3D modelling, spatial analysis, interactive visualisation and the testing of design solutions in digital or mixed environments. In landscape design, VR is used to analyse the

scale of the site, the topography, the balance between open and enclosed areas, the placement of plantings, small architectural features, lighting and materials. A VR model allows the project to be viewed from the user's perspective within the designed environment and enables the design scheme to be compared with anticipated scenarios for the site's use. Working with VR modules can facilitate a quicker understanding of spatial relationships and increase student engagement compared to lectures, 2D drawings and manual modelling (Andalib & Monsur, 2024).

AR can be used to align a digital model with a real or simulated environment. In landscape design, it is used to evaluate the placement of landscape features, the scale of planting schemes, the visual impact of design elements, and the perception of space from different viewpoints. In landscape architecture, AR serves as a tool for analysing spatial relationships between proposed and existing components of the urban environment (Ha *et al.*, 2024). In graphic design, AR is applied to the development of interactive posters, packaging, wayfinding systems, exhibition materials, multimedia objects, and digital visual communications. Within this context, graphic artefacts are considered not merely as static compositions but as elements of user interaction. The integration of AR into graphic design curricula is associated with improved understanding of digital formats, data transformation, cross-platform compatibility, and a shift from two-dimensional to spatial approaches to design (Hu, 2024).

The increasing use of generative and immersive digital technologies in professional practice suggests that they should be regarded as factors contributing to the renewal of educational programmes. According to American Society of Landscape Architects (2025), 55% of practising landscape architects and educators use AI in professional practice, teaching, or research. Consequently, these technologies should be viewed as components of professional training associated with information retrieval, generation of design alternatives, visualisation, presentation of solutions, and communication with clients or project teams. A synthesis of the identified areas demonstrates that AI, VR, and AR perform distinct yet complementary roles in the education of graphic and landscape designers: AI supports the generation and selection of design alternatives, VR provides opportunities for spatial evaluation of solutions, and AR connects digital models with real or simulated environments (Table 1).

Table 1. Areas of application of AI, VR, and AR in the training of graphic and landscape designers

Technology	Application in the educational process	Application in professionally oriented projects	Skills developed
AI	Generation of visual ideas, selection of stylistic approaches, and development of compositional alternatives	Preparation of concepts, visual scenarios, and alternative forms of project presentation	Alternative design development, critical selection, and justification of design decisions
VR	Creation and analysis of 3D models, assessment of scale and spatial relationships	Immersive presentation of landscape objects, parks, and public spaces	Spatial thinking, analysis of user perception, and design validation
AR	Development of interactive posters, packaging, and wayfinding elements	Evaluation of digital objects within real or simulated environments	Interactive visualisation, work within mixed environments, and user interaction

Table 1. Continued

Technology	Application in the educational process	Application in professionally oriented projects	Skills developed
AI+VR/AR	Comparison of design scenarios and their visual evaluation	Preparation of integrated presentations for clients or project teams	Integration of digital tools, interdisciplinary design practice, and professional communication

Source: compiled by the author based on data of A.M. Al-Ansi *et al.* (2023), Landscape Architecture Foundation (2023), O. McGrath *et al.* (2023), S.Y. Andalib & M. Monsur (2024), C. Baker (2024), J. Ha *et al.* (2024), S. Habib *et al.* (2024), N. Hu (2024), American Society of Landscape Architects (2025), S.W. Ee & Z. Tasir (2026)

As shown in Table 1, AI, VR, and AR perform distinct functions within the educational and project-based preparation of designers. AI is primarily associated with the generation, comparison, and preliminary selection of design alternatives, thereby strengthening the analytical stage of idea development. VR provides opportunities for spatial evaluation of solutions, allowing users to assess scale, proportions, pedestrian circulation, and the perception of objects within three-dimensional environments. AR complements this process by aligning digital models with real or simulated surroundings. The combined use of these technologies creates a sequential model of design practice, extending from idea generation and 3D modelling to interactive visualisation, evaluation of solutions, and professional presentation.

The analysis identified AI as a tool for generating visual ideas, selecting stylistic approaches, developing compositional alternatives, and conducting preliminary selection of design solutions. These findings correspond with the results of C.W. Lee (2025), in which the use of generative AI in visual design courses was associated with the development of student creativity through text-based and graphical prompts, as well as through the assessment of flexibility, originality, and the level of detail in design outcomes. Unlike that study, which focused primarily on the influence of AI on students' creative performance, the present research incorporates AI into a broader framework of educational and project-based training, where it functions as a tool for generation, selection, and authorial refinement of solutions. In the present study, AR in graphic design is associated with the development of interactive posters, packaging, wayfinding systems, digital presentations, and visual communication materials. This corresponds with the work of W. Guo *et al.* (2025), in which AR was incorporated into graphic design education through an application model for cultural heritage tourism designed to enhance student engagement and connect visual design with cultural content. In the present study, these findings are generalised more broadly, with AR being considered not only as a means of engaging with cultural heritage but also as a tool for interactive visualisation, user interaction, and evaluation of graphic objects within digital or mixed environments. Furthermore, the present study relates the use of AR in professionally oriented projects to the evaluation of digital objects within real or simulated environments, as well as to the analysis of scale, spatial relationships, and the perception of designed spaces. These findings are consistent with

the conclusions of T.A. Alazzawi & H.A. Alsamer (2024), who associated augmented reality with community participation in design decision-making, support for designers during the selection of solutions, and enhancement of urban environments. In the present study, these conclusions are transferred to the context of graphic and landscape design education, where augmented reality is regarded as a tool for spatial evaluation, comparison of digital models with their surrounding environments, and preparation of projects for professional discussion.

The integration of digital technologies can be regarded as a factor reshaping the structure of the creative process in the education of graphic and landscape designers. The traditional linear sequence of "brief – sketching – refinement – finalisation" is increasingly supplemented by a cyclical model in which the generation of alternatives, their expert evaluation, and subsequent refinement are repeated throughout different stages of the design process. Within a human-AI co-design model, the designer formulates the design intention and prompt, AI generates alternatives, and the human participant subsequently selects, edits, and integrates the results into the project context. This alternation of generation, evaluation, and iteration can enhance the originality of design solutions while maintaining the designer's authorship and control (Wang *et al.*, 2025). As a result, the creative process becomes iterative: rather than progressing directly from a single sketch to a final design, students repeatedly formulate prompts, evaluate generated alternatives, refine them, and develop authorial solutions. In landscape design, this transformation is reflected in the immediate evaluation of design ideas within spatial, environmental, and user-related contexts rather than treating them solely as visual concepts (Andalib & Monsur, 2024).

The implementation of AI, VR, and AR in the studies reviewed is also associated with changes in studio-based learning, where emphasis shifts from assessing only the final product to analysing the design process itself. In this approach, attention is given to problem definition, the logic of digital tool use, the selection of alternatives, and the justification of refinements. In graphic design, AR facilitates the transition from two-dimensional layouts to immersive prototypes, enabling the testing of composition, typography, visual hierarchy, and user interaction across different digital platforms. Such integration is associated with the development of design thinking and problem-solving abilities (Hu, 2024). The role of the lecturer may therefore shift from evaluating outcomes to supporting and monitoring

the design process. Methodological strategies include analysing students' interactions with AI, documenting prompts and iterations, assessing authorial contributions, developing prompt-engineering skills, and incorporating AI literacy modules into educational programmes (Wagner, 2025). In landscape design, AI is employed for site analysis, scenario-based planning, and preliminary visualisation. According to the International Federation of Landscape Architects (2025), 75% of respondents reported increased efficiency in professional tasks through the use of AI, while 71% anticipated significant changes in professional skill requirements within the sector.

The use of AI can also alter the distribution of functions within design activities. Designers retain responsibility for contextual understanding, value-based judgement, ethical evaluation, and the final integration of solutions, whereas AI contributes through the generation of alternatives and the expansion of design possibilities. Human-AI co-design models emphasise that AI may be employed not only for content generation but also for the structuring, comparison, and refinement of design materials. Such integration

supports a more coherent organisation of project outcomes while preserving human control over final decisions (Adobe Research, 2025). In graphic design, this is reflected in the creation of mood boards, the transfer of stylistic characteristics, and the testing of compositional alternatives. In landscape design, AI is used to generate alternative environmental and spatial scenarios that can subsequently be evaluated through VR-based visualisation.

The transformation of educational and project-based activities through digital technologies requires not only proficiency in digital tools but also the development of new professional competencies. As shown in Table 2, these competencies include prompt formulation for AI systems, critical evaluation of generated alternatives, spatial analysis, interactive visualisation, authorship control, and ethical assessment of design decisions. In graphic design, these competencies are reflected in the management of visual alternatives and digital communication formats, whereas in landscape design they are associated with site analysis, scenario-based planning, and the evaluation of solutions within three-dimensional or mixed environments.

Table 2. Emerging professional competencies of graphic and landscape designers under the integration of AI, VR, and AR

Competency group	Content of the competency	Significance for graphic design	Significance for landscape design
Working with AI	Prompt formulation, generation of alternatives, and critical evaluation of outputs	Creation of visual hypotheses, mood boards, and alternative compositions and stylistic solutions	Development of layout, zoning, and spatial organisation scenarios for sites and landscapes
Project analytics	Comparison of alternatives, assessment of suitability to the task, and justification of design choices	Assessment of readability, visual hierarchy, and suitability for the target audience	Evaluation of scale, circulation routes, functional zones, and user scenarios
Immersive modelling	Work within VR and AR environments and interactive validation of solutions	Development of interactive posters, packaging, wayfinding systems, and digital presentations	Spatial validation of landscape features, parks, and public spaces
Authorship control	Documentation of work stages and recording of prompts and subsequent refinements	Justification of individual authorship when using AI	Justification of design decisions with regard to site context
Ethical literacy	Understanding issues of authorship, algorithmic bias, and the standardisation of solutions	Prevention of formulaic visual language	Consideration of the cultural, environmental, and social context of place
Interdisciplinarity	Integration of design, data, technologies, and domain-specific knowledge	Integration of visual communication with digital formats	Integration of design, ecology, data analysis, and spatial modelling

Source: compiled by the author based on data of S.Y. Andalib & M. Monsur (2024), N. Hu (2024), Adobe Research (2025), International Federation of Landscape Architects (2025), M.G. Wagner (2025), N. Wang *et al.* (2025), K. Fleischmann (2026)

As shown in Table 2, the emerging competencies are associated not only with the technical mastery of AI, VR, and AR, but also with changes in the designer's role within the design process. In graphic design, this is reflected in the management of visual alternatives and interactive communication, while in landscape design it is manifested through site analysis, scenario-based planning, and the spatial evaluation of design solutions. The transformation of creative processes may significantly influence designer education: the traditional studio model is increasingly complemented by a flexible project environment in which students engage with AI, VR, and AR as tools for

exploration, evaluation, and refinement of solutions. Changes in pedagogical approaches and the role of the lecturer are therefore regarded as essential conditions for developing the competencies required for professional practice, including critical thinking, the ability to select and justify design alternatives, and ethical responsibility in the use of AI and immersive technologies.

The analysis identified professional competencies in design as a combination of skills related to AI utilisation, project analytics, critical evaluation of digital outputs, authorship control, ethical literacy, and interdisciplinary design practice. These findings correspond with the results of

Y.M. Fang (2025), in which generative AI was incorporated into a multi-level educational strategy encompassing problem definition, feature identification, keyword extraction, generation of alternatives, and subsequent refinement of solutions. The use of AI was also associated with the development of creativity, critical thinking, practical skills, increased student engagement, greater diversity of ideas, and accelerated iterative processes within project-based learning. Unlike that study, which focused primarily on the strategic integration of generative AI into design education, the present research offers a broader interpretation of these competencies. Here, competencies are understood not merely as the ability to use AI tools, but as a comprehensive system encompassing project analytics, selection and refinement of alternatives, ethical oversight, and the integration of digital outputs into educational and project-based activities. In the present study, engagement with AI is not regarded as a substitute for independent creative exploration, but rather as a competency requiring the preservation of student autonomy, an understanding of the logic underlying digital outputs, and the ability to justify individual design decisions. This perspective is consistent with the work of A. Al-sadi & D. Miller (2026), in which human-centred explainable AI was associated with supporting novice designers, enhancing creative self-efficacy, improving idea quality, and preserving user autonomy during interaction with generative systems. The present study extends these conclusions to the broader context of graphic and landscape design education, where authorship control is incorporated into the system of professional competencies alongside critical evaluation, documentation of design stages, ethical assessment, and justification of design decisions. Furthermore, the study links professional competencies to the ability to employ digital technologies for the generation, analysis, visualisation, and evaluation of design solutions while maintaining critical judgement of outcomes. This finding corresponds with the systematic review conducted by W. Rong *et al.* (2025), which associated applications of generative AI in higher art education with expanded learning opportunities, support for creative activity, and changes in the ways students interact with digital artistic tools. Unlike that review, which focused primarily on generative artistic applications in higher education, the present study specifies these implications for the education of graphic and landscape designers through a framework of competencies that includes AI utilisation, project analytics, immersive modelling, authorship control, ethical literacy, and interdisciplinary collaboration.

The use of generative AI in the education of graphic and landscape designers may be associated with the risk of standardising visual language. Since these models are trained on extensive collections of existing images, the outputs they generate may reproduce common compositional structures, stylistic conventions, and visual patterns. Excessive reliance on AI can diminish the role of independent design exploration, resulting in outcomes that exhibit characteristics of standardisation and repetition (Alkhateeb *et al.*, 2026). In graphic design, this risk may be reflected in

similarities of compositional approaches, colour palettes, visual effects, and overall aesthetic qualities. When students begin the design process with automated generation rather than with an analysis of the design brief, target audience, and communication objectives, the development of manual skills, compositional thinking, and conceptual analysis may be weakened. The overuse of AI tools has been identified as a factor that may reduce foundational professional abilities, including manual refinement and in-depth conceptual thinking (Match, 2024). In landscape architecture, the risk may be associated with a weakening of the contextual basis of design decisions. AI can generate visually complete planning solutions; however, such outputs do not always adequately account for topography, soil conditions, climate, vegetation, cultural context, user scenarios, and the social characteristics of a site. Within professional practice, concerns have been expressed regarding the potential reduction of the human dimension in design as AI adoption increases (Canadian Society of Landscape Architects, n.d.).

A long-term limitation of generative systems lies in their dependence on existing datasets and previously established visual models. This may reduce the diversity of unconventional solutions and contribute to increased visual standardisation. Studies examining the use of AI in graphic design have noted that, alongside gains in efficiency, attention must also be paid to the risks of repetition and diminished originality in design outcomes (Zhou *et al.*, 2025). The application of digital technologies is also associated with ethical and legal concerns. One of the principal issues involves the use of copyrighted materials in the training of generative models without the consent of rights holders. In educational settings, this creates risks when AI-generated images are incorporated into portfolios, academic projects, and public presentations, as the provenance of visual materials and the extent of the student's contribution may not be transparent (Altaf, 2024). Ethical challenges include algorithmic bias, questions of authorship, and breaches of academic integrity. Model bias may reproduce cultural, gender-based, or social stereotypes within educational and project materials. Issues of authorship arise when generated outputs are presented as independent work without acknowledging the role of AI in their creation. Consequently, educational programmes require procedures for documenting prompts, stages of generation, selection processes, and subsequent refinements. Questions concerning learner autonomy, informed use of AI, and the right of students to decline the use of such technologies are among the central ethical considerations in digital education (Strunk & Willis, 2025). VR and AR present additional limitations related to physiological and psychological demands. Extended periods of work within immersive environments may lead to cybersickness, disorientation, and visual fatigue. These factors should be considered when determining session duration, assignment structures, and conditions for the use of immersive technologies in educational contexts (Skulmowski, 2023). A further concern is digital inequality. Access to AI tools, VR equipment, AR platforms, and

high-performance hardware varies considerably among educational institutions and individual students. Such disparities may exacerbate differences in educational quality unless the implementation of emerging technologies is accompanied by organisational regulation, equitable access policies, and transparent criteria for assessing individual contributions to project work.

The integration of AI, VR and AR into professional practice in graphic and landscape design can be seen as a basis for refining the content of educational programmes. According to the Future of Jobs Report 2025, some routine tasks in the creative industries may be automated, whilst the importance of creative thinking, AI literacy and the ability to solve complex problems is increasing (World Economic Forum, 2025). In light of this, it is advisable for graphic design courses to include assignments involving the formulation of briefs, the critical selection of generated images, the assessment of visual hierarchy, the adaptation of layouts and the justification of the designer's creative contribution. In the training of landscape designers, these changes can be incorporated through assignments involving site analysis, scenario-based design, spatial verification of solutions in a virtual environment, and the comparison of digital models with the real-world context. AI, VR and AR should therefore be viewed not only as professional visualisation tools, but also as a factor in updating the content of academic disciplines, assessment criteria and forms of project work.

In graphic design, the positions most susceptible to automation are those involving routine layout production, preparation of simple visual materials, adaptation of existing designs, and creation of standardised imagery. For such tasks, AI reduces the need for manual execution of repetitive operations. At the same time, the importance

of competencies related to managing human-AI collaboration, strategic thinking, contextual understanding, and the evaluation of generated outputs continues to grow. For certain professional roles, the risk of displacement has been estimated at up to 41% (Match, 2024). In landscape architecture, the level of automation is comparatively lower because site design requires consideration of topography, ecology, climate, social scenarios, regulatory frameworks, and local context. Nevertheless, the nature of professional tasks is also evolving. AI is increasingly used for site analysis, scenario-based planning, and the preparation of visualisations for clients. According to professional surveys, 71% of practitioners anticipate changes in the skill sets required within the profession, while 75% report that AI is already influencing management processes and decision-making within the sector (Canadian Society of Landscape Architects, n.d.). Consequently, the influence of AI, VR, and AR on the labour market is manifested not through the direct replacement of professions but through the redistribution of professional functions. The proportion of routine technical operations is decreasing, while analytical, strategic, ethical, and interdisciplinary competencies are becoming increasingly significant. For designer education, this implies the need to orient educational programmes towards AI literacy, engagement with immersive environments, critical evaluation of digital outputs, and the preservation of authorship control over design decisions. Alongside the educational and project-related opportunities offered by digital technologies, their integration is accompanied by a range of methodological, ethical, legal, and organisational risks. These factors should be carefully considered when designing educational assignments, developing assessment criteria, and establishing guidelines for the use of digital tools (Table 3).

Table 3. Risks associated with the integration of AI, VR, and AR into the training of graphic and landscape designers

Risk category	Manifestation in graphic design	Manifestation in landscape design	Possible pedagogical regulation
Uniformity of visual language	Repetition of compositions, colour schemes, stylistic approaches, and visual effects	Generation of standardised visual solutions without considering site-specific characteristics	Comparison of AI-generated alternatives with original sketches and mandatory justification of design choices
Reduction of independent design exploration	Commencing work with content generation rather than analysis of the design task and target audience	Replacement of site analysis with the formal generation of layout alternatives	Introduction of a preliminary analysis stage prior to the use of AI
Issues of authorship	Unclear extent of individual authorship in layouts, posters, branding, or packaging designs	Unclear extent of individual authorship in planning scenarios and landscape visualisations	Documentation of prompts, generation stages, selection processes, and subsequent refinements
Algorithmic bias	Reproduction of cultural, gender, or social stereotypes in visual imagery	Insufficient consideration of the local cultural and social context	Critical evaluation of generated outputs and discussion of ethical constraints
Legal risks	Use of images of uncertain origin in portfolios and public projects	Use of visualisations without transparent disclosure of sources and the role of AI	Rules for citation, labelling of AI-generated content, and its use in portfolios
Physiological strain associated with VR and AR use	Visual strain resulting from prolonged interaction with immersive environments	Disorientation or cybersickness caused by prolonged exposure to VR environments	Limitation of VR/AR session duration and alternation between different modes of work
Digital inequality	Unequal access to AI platforms, AR technologies, and high-performance devices	Unequal access to VR equipment and spatial modelling software	Equal access conditions, laboratory-based learning, and institutional support

Source: compiled by the author based on data of Canadian Society of Landscape Architects (n.d.), A. Skulmowski (2023), A.R. Doshi & O.P. Hauser (2024), S. Altaf (2024), R. Match (2024), V. Strunk & J. Willis (2025), S. Zhou *et al.* (2025), World Economic Forum (2025), S. Alkhateeb *et al.* (2026), L. Eaves & J. Adair (2026), Organisation for Economic Co-operation and Development (2026)

As shown in Table 3, the main risks associated with the integration of AI, VR and AR relate to the standardisation of design solutions, a reduction in independent analysis, uncertainty regarding authorship, legal and ethical constraints, and unequal access to digital tools. In graphic design, these risks are more commonly manifested in the repetitiveness of visual language and the use of AI-generated content, whilst in landscape design they manifest as insufficient consideration of the site's specific characteristics and the user context. These risks can be mitigated through preliminary analysis of the task, documenting the stages of working with AI, mandatory justification of solution choices, and transparent rules for the use of digital technologies.

The analysis identified the risks associated with the integration of AI, VR, and AR in terms of authorship issues, reduced originality, algorithmic bias, legal uncertainty, and the unclear provenance of digital content. These findings correspond with the results of K.A. Bartlett & J.D. Camba (2024), who associated the use of generative AI in product design education with ethical and legal concerns, including bias, hidden labour, appropriation of artists' works, lack of originality in generated outputs, and the absence of comprehensive copyright protection for AI-generated images. Unlike their study, which focused primarily on product design and generative imagery, the present research extends these risks to the training of graphic and landscape designers and supplements them with pedagogical mechanisms, including the recording of prompts, documentation of generation stages, selection of alternatives, and justification of authorial refinement. In the present study, issues of authorship and academic integrity are considered among the principal risks associated with the use of AI in educational projects. This position is consistent with the work of M.B. Huh *et al.* (2025), in which architecture and interior architecture students' perceptions of generative tools were linked to ethical responsibility, educational value, career implications, authorship, and the visual representation of design outcomes. The present study broadens these conclusions by considering AI use not only from the perspective of student perceptions but also within the framework of pedagogical regulation, where transparent rules for identifying AI-generated content, documenting the degree of technological involvement, and assessing students' independent contributions are required. Furthermore, the present study associates the risks of VR with the need for methodological limitations on its use, since immersive environments require consideration of session duration, technical accessibility, the quality of learning scenarios, and potential physiological strain. These findings correspond with the bibliometric review conducted by A. Çalışkan & S.G. Kayaakdag (2025), in which virtual learning environments in architecture and design education were described as an emerging field associated with project-based learning, immersive interaction, and the need for more sustainable pedagogical models. The present study further specifies these conclusions through a framework of risks and pedagogical regulation, including limiting the duration of work

in virtual environments, alternating instructional formats, ensuring access to appropriate equipment, and incorporating virtual reality only into tasks where it supports spatial evaluation and professional discussion of design projects.

The balanced integration of AI, VR and AR into the training of graphic and landscape designers requires a combination of digital and fundamental design practices. It is advisable to include modules in educational programmes on formulating prompts for AI, the critical selection of generated options, AI ethics and the assessment of the quality of digital outputs (Wagner, 2025; Digital Education Council, 2026). Preserving traditional design practices also remains an essential requirement for training designers. Assignments utilising AI should be alternated with manual sketching, model-making, conceptual analysis and the independent development of design ideas without automated generation. This helps to maintain a link between digital tools, core professional skills and original design thinking. Transparency in the design process is of particular importance. In academic assignments, it is essential to document the prompts given to the AI, the stages of generation, the selection criteria, the nature of any refinements and the extent of the student's original contribution. Such requirements help to distinguish between the use of digital tools and independent design solutions, whilst also reducing the risks of breaches of academic integrity and copyright. In landscape design, the integration of AI must be accompanied by an analysis of environmental data, the social context, user scenarios and the physical characteristics of the site. Digital modelling should therefore be combined with site surveys, field observations, prototyping and environmental impact assessments. In graphic design, a similar requirement is to evaluate generated solutions in terms of their communicative purpose, visual hierarchy, target audience and conditions of use. The ongoing training of teaching staff is a prerequisite for the implementation of AI, VR and AR. It must include the systematic exploration of the technologies' capabilities, an analysis of their limitations, the development of criteria for evaluating digital projects, and the establishment of guidelines for the use of AI in the educational environment. This approach helps to avoid situations in which technologies are employed merely as technical additions without methodological justification. Thus, the risks associated with automation do not require a rejection of AI, VR and AR, but rather methodological regulation of their use. In the training of designers, it is advisable to regard these technologies as tools for design exploration, visualisation and the testing of solutions, whilst maintaining creative control, ethical responsibility and contextual analysis.

CONCLUSIONS

The theoretical-analytical study demonstrated that AI, VR, and AR are transforming the content of graphic and landscape design education by expanding opportunities for design exploration, enhancing visualisation, and facilitating more interactive forms of design evaluation. Within

the educational process, AI is used for generating visual ideas, selecting stylistic approaches, developing compositional alternatives, and conducting preliminary selection of design solutions. VR is employed for the creation and analysis of 3D models and for assessing scale, proportions, and spatial relationships. AR enables the development of interactive objects and the alignment of digital models with real or simulated environments. It was found that in professionally oriented projects, AI supports the preparation of concepts, visual scenarios, and alternative forms of project presentation. VR is applied to immersive presentations of landscape elements, parks, and public spaces, whereas AR is used to evaluate digital objects within their intended environments. The combined use of AI, VR, and AR creates an integrated model of design practice encompassing idea generation, 3D modelling, interactive visualisation, solution evaluation, and professional presentation.

The analysis indicated that the integration of digital technologies requires the development of new professional competencies. These include proficiency in AI applications, project analytics, immersive modelling, authorship control, ethical literacy, and interdisciplinary collaboration. In graphic design, these competencies are associated with the management of visual alternatives, digital communication formats, and interactive objects. In landscape design, they relate to site analysis, scenario-based planning, spatial evaluation of solutions, and consideration of user context. At the same time, the study identified several risks associated with the integration of generative and immersive

technologies, including the standardisation of visual language, reduced independence in design exploration, ambiguity regarding authorship, algorithmic bias, legal constraints, physiological effects associated with VR and AR, and digital inequality. These risks can be mitigated through methodological regulation, including preliminary analysis of the design task, documentation of AI prompts, recording of generation and refinement stages, preservation of hand sketching practices, and the introduction of ethical guidelines governing the use of digital content. Accordingly, AI, VR, and AR should be regarded not as substitutes for fundamental design training, but as tools for generating, visualising, evaluating, and presenting design solutions while maintaining authorship control, critical analysis, and a context-sensitive approach. Future research should focus on empirically examining the influence of AI, VR, and AR on the quality of design outcomes, the development of professional competencies, the independence of design exploration, and the establishment of assessment criteria for educational projects involving digital technologies.

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