

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.

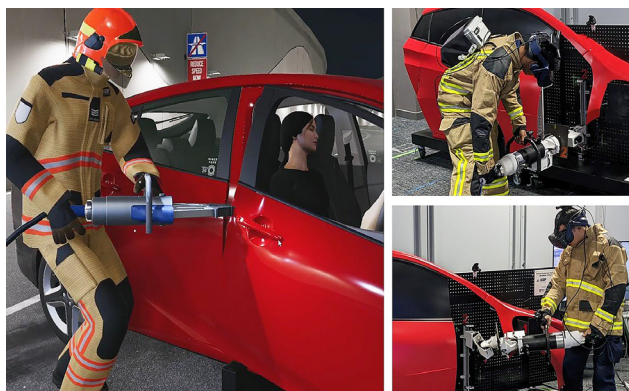


Figure 1. XR simulation environment for training rescuers within the “Training boost for emergency responders through XR” project (NUS, Singapore)

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.

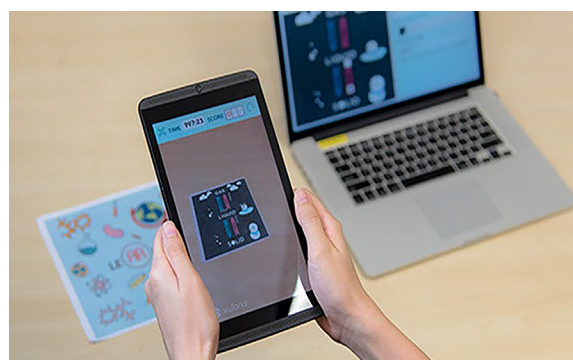


Figure 3. The LeARNus student AR platform for creating interactive learning environments at NUS
Source: compiled by the author based on Keio-NUS CUTE Center (n.d.a)

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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