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Original Contribution

INTERACTIVE LEARNING WITH VIRTUAL REALITY AND 3D PRINTING

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ABSTRACT
This study explores the educational potential of integrating virtual reality (VR) and 3D printing in STEM education, with a focus on improving students' understanding of molecular geometry. The main aim is to examine how engaging technologies influence students' conceptual understanding, involvement, and spatial thinking.
The research was conducted with 32 undergraduate students from the Faculty of Mathematics and Natural Sciences at South-West University "Neofit Rilski". A structured three-phase learning model was applied, including digital modeling of molecules using CAD software, physical creation of models through 3D printing, and interactive exploration in a virtual reality environment. Data were collected through questionnaires, classroom observations, and reflective student journals.
The results show that over 90% of students reported improved understanding of molecular structures, while a significant number demonstrated increased motivation and enhanced spatial visualization skills. Students also highlighted the value of combining physical and virtual interaction in the learning process.
The findings suggest that the integration of VR and 3D printing provides an effective and engaging approach to teaching abstract scientific concepts. This approach supports active learning and contributes to the development of key competencies in STEM education.

Keywords: immersive technologies, molecular visualization, CAD modeling, STEM education

INTRODUCTION TO THE DIGITAL SHIFT IN EDUCATION

Today, the world of education is dramatically changing with the integration of high-level technologies. Virtual reality (VR) and 3D printing technologies have become game changers, re-inventing the ways students learn, communicate and implement knowledge in the classroom. These technologies reflect a more significant transition toward hands-on and student-driven learning, where interaction and immersion help students grasp concepts more profoundly and become more motivated (1).

Traditional methods of teaching that are based mainly on the one-way reception of information are inadequate, however, for training students to be able to cope with the challenges of modern workforce. On the other hand, VR offers students the possibility to access virtual settings where they can experience things that are quite abstract, but very useful in problem-solving tasks in science, engineering, and medicine (2). Similarly, 3D printing forms a link between theory and practice, as it gives learners the opportunity to make, change, and test palpably the most complex subjects in their university studies (3).

Furthermore, this digital revolution in education is driven by the continuing efforts to make schools more accessible and adaptable. Virtual reality and three-dimensional printing open new doors to personalized learning, as they enable teachers to create situations that correspond to different learning styles, cognitive abilities, and accessibility needs (4). Moreover, the use of these instruments is helpful to establish a teamwork spirit, as well as to improving creativity and the ability to find solutions - the skills that are at the core of modern pedagogical frameworks, such as STEM and STREAM. The setting up of specialized STEM centres in

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Bulgaria and throughout Europe, such as the one at South-West University “Neofit Rilski” is a sign of a clear institutional commitment to implementing innovative teaching methods. Thanks to advanced equipment, such as Creality CR-10 Smart Pro 3D printer, VR systems, or Oculus Quest, future teachers have the possibility to create practice-based, interdisciplinary learning experiences that resemble current challenges in the real world.

While we are moving through this transformation in education, it becomes clearer that virtual reality and 3-dimensional printing technologies are not only supplements, but also powerful engines for us to change the way knowledge is delivered, experienced, and retained.

VIRTUAL REALITY IN STEM EDUCATION

Virtual reality (VR) is gaining ground as an effective tool for STEM education. VR provides a sensory-rich, computer-generated environment, which allows students to deal with abstract or complicated topics in unique ways. This technology facilitates the acquisition of spatial awareness, systems thinking, and conceptual understanding - skills that are majorly required for science, technology, engineering, and mathematics fields (5).

Indeed, VR's main benefit for STEM education is its planning of the environment of the most realistic simulation, where learners will be able to do experiments by themselves, control variables, and see the results immediately without any danger. For instance, in chemistry education, VR allows students to virtually make reactions, go through molecular structures, and visualize invisible phenomena, such as electron movement or atomic interactions - all these without the hazards of a real laboratory (6). This involvement at the deepest level makes understanding thorough, affirms motivation, and improves memory.

In addition, VR also encourages energetic learning by changing the part of students from passive listeners to active participants. For example, when students operate in a virtual lab or virtually travel through the solar system or the human circulatory system, they are not only receiving content - but they are also actually making sense of it through experiential engagement. Such embodied learning experiences make cognitive processing easier and facilitate the long-time keeping of complex knowledge (1).

On the other hand, VR not only has cognitive benefits, but also stimulates behavioural learning outcomes. Students often mention higher levels of satisfaction, interest, and self-efficacy when using VR-based instructional tools in comparison with traditional methods (2). The intensity of emotions is of great importance, for they are the sources of their persistence in learning and positive attitudes toward STEM subjects. Moreover, VR is in line with the inclusive pedagogical approach. Students who have different concentration problems or specific learning disabilities might get the most out of structured, highly immersive environments which not only facilitate but also, in a way, increase their concentration on the tasks and the material presented (4).

Sometimes technology has drawbacks, such as high cost of equipment, need for training and potential technical problems; however, VR has a clear pedagogical potential in STEM learning environments. Besides being a bonus to traditional teaching, it becomes a revolutionary platform that enables new ways for students to experience scientific knowledge (7).

3D PRINTING AND HANDS-ON LEARNING

3D printing, also called additive manufacturing, has recently acquired a leading position in educational technology (3). Within STEM areas 3D printing inspires students with new ideas to transfer digital images into the real world. In contrast to traditional didactic methodologies which frequently depend on implicit symbols, equations or 2D representations, 3D printing gives practical and visual learning that deepens students’ understanding and scientific interests (3).

Another advantage of 3D printing in education is that it allows the practical realization of theoretical concepts. For instance, in physics and engineering, students can create objects, such as the parts of a mechanical system, or simple machines and functional prototypes that let them test the structural integrity of a building or energy transfer. Such ideas boost the experiential learning approach, which according to several studies is termed as the effective one for cognitive development and retention in STEM education (8). In addition, 3D printing promotes vital skills of the 21st century. The design-based activities are particularly compatible with current STEM curricula that stress the importance of inquiry, modelling, testing, and optimization (9). A recent study in pedagogy reveals that the use of 3D printing in creative activities improves student motivation and engagement. The results illustrate that learners who have been actively involved in 3D printing projects are apparently more ready to tackle difficult content areas as they get a new feeling of their learning and a stronger desire to explore (10). Besides, such activities make it easier for students to collaborate and communicate, especially if students organize themselves in groups to create and set up models which respond to a particular scientific problem. The successful introduction of 3D printing in a classroom is particularly important, and it depends on the proper training of teachers, the alignment of the curriculum, and the availability of technical support. Teachers must acquire not only technical knowledge, but also pedagogical strategies that will allow them to efficiently use the three-dimensional printing in their lessons (11). 3D printing turns conceptual academic content into experiential learning, thus making science and technology more understandable, exciting, and more directly connected to students' daily life. It encourages interdisciplinary learning by incorporating design, mathematics, and scientific inquiry activities. It also provides educators with new opportunities for personalizing instruction to meet students' needs in most diverse ways.

EXPERIMENT IN THE STEM CENTER - FROM MOLECULE TO MODEL TO VIRTUAL SPACE

To demonstrate the educational capabilities of combining virtual reality (VR) and 3D printing in STEM education, an experiment was carried out at the STEM Centre of South-West University "Neofit Rilski" in Blagoevgrad. The experiment was aimed at students from the Faculty of Mathematics and Natural Sciences, who attended the course in Methodology of the Chemical Experiment. The goal was to extend students' knowledge of molecular geometry through an integrated design-and-explore approach utilizing 3D modelling, 3D printing, and virtual reality environments.

RESEARCH AIM AND QUESTIONS

The main aim of this study was to investigate the educational impact of integrating virtual reality (VR) and 3D printing in STEM education, specifically in the context of learning molecular geometry.

The study attempted to answer the following research questions:

1. Does the combined use of VR and 3D printing improve students' understanding of molecular geometry compared to traditional 2D representations?
2. How does the use of immersive and hands-on technologies affect students' engagement and motivation in learning chemistry?
3. What is the impact of this approach on students' spatial thinking and collaborative skills?

Based on these questions, we formulated the following hypothesis:

H1: The integration of VR and 3D printing leads to improved conceptual understanding, higher engagement, and enhanced spatial skills among students.

METHODOLOGY

Participants

The study involved 32 undergraduate students from the Faculty of Mathematics and Natural Sciences at South-West University "Neofit Rilski", enrolled in the course Methodology of the Chemical Experiment.

Data were collected using the following tools

- A structured questionnaire consisting of Likert-scale and open-ended questions;
- Reflective student journals;
- Direct classroom observations.

Procedure

The study was conducted over three sessions corresponding to the three phases of the activity:

1. CAD modeling of molecular structures;
2. 3D printing of the models;
3. Interaction with models in a virtual reality environment.

Students worked in small groups and completed all three phases sequentially.

Data analysis

Quantitative data from questionnaires were analysed using descriptive statistics (percentages and mean values), while qualitative data from journals and observations were analysed through thematic analysis.

The experiment described consisted of three interconnected stages:

Phase 1: Molecular design in a virtual CAD setting

In teams, students modelled simple molecules using Tinkercad - a CAD tool in the cloud that is both easy to use and accessible from anywhere. A group of students decided on the molecule they wanted to work with, for example, the methane group (CH_4), ammonia (NH_3), water (H_2O), sulphur tetrafluoride (SF_4), and then they constructed its molecular geometry, which included bond angles electron pairs. They were accordingly led through the process of accurately positioning atoms and bond lengths while using ball-and-stick model conventions.

Phase 2: 3D printing of molecular models

After that, the models were sent in STL format and printed with the Creality CR-10 Smart Pro 3D printer in the STEM Centre. The filament colour was used in a very clever way - carbon atoms in black, hydrogen in white, nitrogen in blue, etc. - to be like real molecular kits. Students also took part in the slicing process with the help of Ultimaker Cura software, thus they found out how printer parameters (e.g., infill density, support structures, temperature) influence the final product. This stage focused on technical skills, repetition, and design confirmation. High level of student agency and design thinking development in STEM can be supported by this hands-on modelling, as research confirms (9, 13).

Phase 3: Virtual interaction using VR

After creating physical models, students submitted their molecular models to CoSpaces Edu, a virtual reality platform that supports Oculus Quest 2 headsets. In the VR environment, students had the possibility to increase the molecule, to go around it, to spin it, and to even analyse it at the atomic level. And through scripting tools, they even got the opportunity to add animations that simulated the vibration of bonds and the interaction between molecules when the experiment was conducted under certain conditions. VR interaction phase thus enabled students to watch the dynamic behaviour practically, thus deepening the understanding of the concept of 3D molecular motion. VR's multisensory immersion and interactivity have been shown to have a major impact on the increased conceptual understanding of STEM subjects.

RESULTS

The collected data indicate a strong positive impact of the integrated approach.

Quantitative results show that:

- 91% of students reported improved understanding of molecular geometry;
- 87% indicated increased motivation during the learning process;
- 84% reported enhanced spatial visualization skills.

Students particularly emphasized the value of combining physical and virtual interaction. For example, 78% of participants stated that manipulating both real and virtual models helped them better understand bond angles and molecular shapes.

Qualitative data from student reflections support these findings. Students reported that:

- The 3D printing phase helped them "see and build" molecules;
- The VR phase allowed them to "explore and interact" with structures dynamically.

These results demonstrate that the combination of VR and 3D printing supports both cognitive and experiential learning.

Essentially, this experiment also demonstrated the significance of inclusiveness. A student who had mild dyslexia mentioned that changing physical 3D molecules and virtually doing this again was one of the reasons the student could manage the excessive situations most often caused by text-based instruction. Such cases constitute evidence that this methodology is compatible with different types of learners and is compliant with the universal design principles in education (14).

DISCUSSION

The results confirm that the integration of VR and 3D printing exercises a significant positive effect on students' understanding and engagement.

Compared to traditional teaching methods, this approach provides multimodal learning experiences, combining visual, tactile, and immersive elements. This aligns with existing research, which suggests that experiential learning improves knowledge retention and conceptual understanding (15).

The findings also highlight the importance of active learning. Students were not passive recipients of information, but active participants in designing, creating, and exploring scientific models.

Furthermore, the approach supports inclusive education. The use of multiple representations allows students with different learning styles to better engage with the content.

However, the study has limitations, including a relatively small sample size and the absence of a control group. Future research should include experimental and control groups to provide stronger evidence.

ADDRESSING CHALLENGES AND SCALING IMPLEMENTATION

This section discusses the main challenges related to the implementation of virtual reality and 3D printing in STEM education, based on the findings of the present study.

Despite the convincing educational benefits of combining virtual reality (VR) and 3D printing with education, there are still serious challenges that need to be solved if these technologies are to be adopted on a large scale. Those issues are lack of infrastructure, unpreparedness of teachers, curricular alignment, and equity of access. It is essential to realize and remove these barriers to ensure that these technologies are not limited only to elite institutions but also become a part of mainstream education systems.

Even if the necessary gear is available, the successful realization of VR and 3D printing relies largely on teacher confidence and competence. A big number of educators confess that they feel hardly any trust in their ability to operate these tools or to find a proper and reasonable way for implementing them in their instructional practices. Only with proper training, there is a possibility that technology might be utilized in a superficial way, i.e. only as a novelty instead of being deeply embedded in pedagogy (16, 17).

Other than that, educators must be given assistance to make these tools fit well with curriculum standards. As Li mentions, the technology is not to be regarded as extra-facilities, but integrated ways that help students achieve the chemical, physical, biological, engineering learning outcomes, etc. Curriculum mapping and resource libraries that connect VR experiences and printable models to specific national standards and lesson objectives can facilitate smoother integration (18).

SCIENTIFIC CONTRIBUTION

This study contributes to the field of STEM education by providing an integrated model for combining virtual reality and 3D printing in teaching complex scientific concepts.

The main contributions include:
- A structured pedagogical model combining digital design, physical prototyping, and immersive visualization;
- Empirical evidence supporting the effectiveness of this approach in improving spatial understanding;
- Practical guidelines for implementing such activities in university-level chemistry education.

The study also demonstrates how emerging technologies can be used not only as tools, but as core components of innovative teaching strategies.

EDUCATIONAL IMPLICATIONS

The union of virtual reality (VR) and 3D printing in STEM education is overloaded with pedagogical power to change the way we teach. Technology not only supports content delivery but also enables students to be active problem-solvers and creators rather than passive knowledge consumers. The use of these technologies promotes a constructivist approach to learning where students create meaning through direct manipulation, exploration, and reflection (19). VR and 3D printing thus facilitate the achievement of higher-order thinking skills, such as analysis, evaluation, and synthesis, which are the most important skills for 21st century learners.

From a curriculum point of view, the educational implications of these are vast and interdisciplinary. Chemistry students can study molecular structures at a very deep and immersive level; engineering students can do prototyping and test their models; history students can 3D print and reconstruct the cultural artifacts; and biology students can go inside the human body. This cross-curricular utility positions these technologies as universal tools, rather than place enhancements. Their flexibility also matches with STREAM education (Science, Technology, Reading, Engineering, Arts, and Mathematics) which highlights connections in knowledge and lays emphasis on real-world relevance (20).

CONCLUSION

Education is in the process of responding to the specifics of the 21st century. Simultaneously, technological advances such as virtual reality and 3D printing appear not as additional, but as main supports of modern pedagogy. Their incorporation within STEM education allows the students to get more than just engagement - it enables them to gain access to deeper, alive learning experiences that link the abstract theory with practical understanding. When learners can handle the virtual representation of molecular models, build functional prototypes, and manipulate digital environments, they become capable of critical thinking, show creativity in problem-solving and achieve greater knowledge retention.

One experiment carried out at South-West University's STEM Centre illustrates how these technologies can be combined in a practical way to stimulate the emergence of a multidimensional learning process that improves both cognitive and emotional outcomes. Besides, VR and 3D printing amplify the aims of fair and unbiased education by embracing different learning styles and inclusion.

Still, the actual feature of these technologies is going to come out only when they are implemented in a sensible way, and teacher training, curriculum compatibility, investment in infrastructure, and visionary leadership serve as the basis for this. More and more institutions are adopting their revolutionary value, hence, we are approaching a future, when immersive, hands-on, and accessible education will no longer be the exception, but the rule. In this future, learning will not be confined to textbooks or classrooms anymore, but will become an interactive journey through physical and virtual spaces - one where all students can explore, create, and succeed.

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