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COMPARATIVE ANALYSIS OF THE EFFECTIVENESS OF SIMULATION AND REAL LABORATORY EXPERIMENTS IN OPTICS EDUCATION

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Abstract. *This article provides a comparative analysis of the educational effectiveness of simulation (virtual) laboratories and traditional real laboratory experiments in teaching optics. The study examined the level of understanding of students , cognitive load, formation of practical skills and motivation indicators as the main indicators. The results show that simulation laboratories are effective in quickly and visually mastering theoretical concepts, while real laboratories have an advantage in forming practical skills. The highest effectiveness was observed in the blended approach.*

Keywords : *optics, simulation, virtual laboratory , real experience, didactics, cognitive load, STEAM*

OPTIKA TA'LIMIDA SIMULYATSIYA VA HAQIQIY LABORATORIYA TAJRIBALARINING SAMARADORLIGINI TAQQOSLASH TAHLILI

Annotatsiya: *Ushbu maqolada optika fanini o'qitishda simulyatsiya (virtual) laboratoriyalar va an'anaviy real laboratoriya tajribalarining ta'limiy samaradorligi qiyosiy tahlil qilinadi. Tadqiqotda talabalar bilimini tushunish darajasi, kognitiv yuklama, amaliy ko'nikmalarni shakllantirish va motivatsiya ko'rsatkichlari asosiy mezonlar sifatida o'rganildi. Natijalar shuni ko'rsatdiki, simulyatsiya laboratoriyalari nazariy tushunchalarni tez va vizual tarzda o'zlashtirishda samarali, real laboratoriyalar esa amaliy ko'nikmalarni shakllantirishda ustunlikka ega. Eng yuqori samaradorlik aralash (blended) yondashuvda kuzatildi.*

Kalit so'zlar: *optika, simulyatsiya, virtual laboratoriya, real tajriba, didaktika, kognitiv yuklama, STEAM.*

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ЭФФЕКТИВНОСТИ СИМУЛЯЦИОННЫХ И РЕАЛЬНЫХ ЛАБОРАТОРНЫХ ЭКСПЕРИМЕНТОВ В ОБУЧЕНИИ ОПТИКЕ

Аннотация: *В данной статье представлен сравнительный анализ образовательной эффективности симуляционных (виртуальных) лабораторий и традиционных реальных лабораторных экспериментов в обучении оптике. В качестве основных показателей были рассмотрены уровень понимания студентами, когнитивная нагрузка, формирование практических навыков и показатели* *мотивации. Результаты показывают, что симуляционные лаборатории эффективны для быстрого и наглядного усвоения теоретических понятий, тогда как реальные лаборатории имеют преимущество в формировании практических навыков. Наивысшая эффективность наблюдается при смешанном (blended) подходе.*

Ключевые слова: *оптика, симуляция, виртуальная лаборатория, реальный эксперимент, дидактика, когнитивная нагрузка, STEAM.*

INTRODUCTION

Innovative and technological approaches play an important role in the teaching of physics, in particular optics . Optical phenomena - the laws of light interference, diffraction, refraction and reflection - are characterized by their abstract nature, and their theoretical explanation alone is not enough to form a complete and deep understanding in students. Therefore, there is an increasing need to study these phenomena through practical experiments or computer-based modeling .

In recent years, the digital transformation process has had a significant impact on the field of education, with the widespread introduction of simulation laboratories (PhET Interactive Simulations, GeoGebra, virtual laboratory environments). These tools allow students to observe complex physical processes in a visual and interactive way, and to gain a deeper understanding of the physical nature of phenomena by changing parameters.

At the same time, traditional real laboratory exercises also retain their didactic value. Real experiments play an important role in developing students' measurement culture, skills in working with equipment, and experimental thinking.

The main goal of this study is to conduct a scientifically based comparative analysis of the effectiveness of simulation and real laboratory approaches in optics education, identify their advantages and limitations, and develop an optimal integrative (blended) didactic model for the learning process .

METHODOLOGY

Research design (improved)

This study was conducted using a quasi-experimental design. This approach is characterized by the fact that it allows for the evaluation of the effectiveness of pedagogical interventions in a natural learning environment and serves to draw scientific conclusions while minimizing the influence of external factors on the learning process.

Two groups were formed within the framework of the study:

Experimental group (EG): students in this group were trained in the optics section using simulation laboratories (PhET Interactive Simulations, virtual modeling tools, and digital learning environments). This approach was aimed at increasing students' cognitive activity through visualization, interactivity, and the ability to dynamically change parameters ;

Control group (CG): Students in this group were taught using traditional real-world laboratory experiments. This approach focused on working with real equipment, making physical measurements, and developing experimental skills .

Both groups were given the same content , sequence of topics, and learning objectives. The study used the teaching aids (simulation vs. real laboratory) as the main independent variable , and the dependent variables were students' knowledge level, comprehension index, practical skills, and motivation level. This allowed a comparative analysis of the differences between the pedagogical approaches on a scientific basis .

Experimental group (EG): students were trained using simulation laboratories (PhET, virtual models, and digital environments);

Control group (NG): Students were trained based on traditional real-world laboratory experiments.

Both groups were provided with the same learning content, the only differences being in teaching tools and methodological approaches.

Research object (improved)

were students of grades 10–11 of academic lyceums. This selection was based on the students' sufficient basic knowledge of physics and the level of cognitive preparation necessary for studying the optics department.

The research covered the main topics of the optics department, including: light interference, diffraction, laws of refraction, as well as lens systems and optical image formation processes. The selection of these topics is explained by their high level of abstraction and the need for experimental and simulation approaches .

To ensure the internal validity of the study, the groups were matched as much as possible in terms of students' initial knowledge level, academic performance, and subject preparation. This process was carried out based on the principle of homogenization and served to minimize external factors affecting the results.

Evaluation criteria (improved)

In order to comprehensively assess the effectiveness of the research, several interrelated pedagogical and psychometric indicators were used. These indicators allowed to fully cover the level of cognitive, practical and affective development of students .

The evaluation was based on the following main criteria:

Knowledge level - students' theoretical knowledge of the optics department was assessed based on the results of pre-test and post-test. This approach allowed us to quantitatively determine the dynamics of mastery in the learning process;

The level of understanding was measured through open and semi-open questions aimed at conceptual thinking, determining cause-and-effect relationships and explaining physical phenomena. This criterion served to determine the level of deep learning of the students ;

Practical skills - the quality of laboratory tasks was analyzed based on a specially developed evaluation rubric. The rubric included criteria for accuracy, correctness, understanding of the experimental process, and interpretation of results**;**

Motivation level — students' interest in learning and intrinsic motivation were assessed using a standardized questionnaire based on the Likert scale. This allowed us to study the impact of the affective component on educational effectiveness;

Cognitive load - the mental load that occurs during the learning process - was determined based on a simplified version of the NASA-TLX (Task Load Index) methodology, and the level of use of students' mental resources was assessed .

INSTRUMENTS (RESEARCH TOOLS)

In this study, several standardized measurement and diagnostic instruments were used to comprehensively assess the knowledge level, cognitive development, and

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affective state of students. These tools served to ensure the reliability and objectivity of the results of the pedagogical experiment .

The following main instruments were used in the study :

Pre-tests and post-tests were used to determine changes in students' knowledge levels in the optics section and to quantitatively assess the effectiveness of teaching. Test tasks had a multi-level structure covering the levels of knowledge, understanding, and application ;

A Likert-scale questionnaire was used to measure students' motivation, interest, and attitude towards the learning process. The questionnaire was based on a 5-point scale and aimed to identify intrinsic motivation and extrinsic motivation factors;

The laboratory assignment rubric is a system of criteria developed to objectively evaluate students' practical activities, assessing accuracy, methodological correctness, quality of execution of the experimental process, and skills in analyzing results .

Analysis method (improved) collected in this study were statistically analyzed using a quantitative approach. The analysis process was aimed at ensuring the reliability, accuracy, and scientific validity of the results of the pedagogical experiment .

Key statistical indicators included:

Mean — used to determine the overall trend of knowledge level, comprehension score, and other indicators for each group;

Variance and Standard Deviation — used to assess the spread of data and the degree of individual differences;

Relative Gain Score — calculated to determine the dynamics of change between pre-test and post-test results, which allowed for a quantitative expression of the effectiveness of training;

Between-group comparison analysis was performed to determine the differences between the experimental and control groups. At this stage, the principle of using t-test (independent samples t-test) or appropriate non-parametric tests was assumed to determine statistical significance.

To increase the reliability of the results, the data were visualized in graphical (bar chart, line graph) and tabular form . This made the results easier to interpret and served to more clearly show the differences between the groups.

RESULTS

The empirical data obtained within the framework of this study allowed for a comparative assessment of the effectiveness of teaching optics between the experimental and control groups. The results are presented below for individual indicators .

Analysis of the pre-test and post-test results showed that both groups showed a significant increase in knowledge. However, the dynamics of growth was higher in the experimental group:

Experimental group (EG): average knowledge growth **+28%**

Control group (NG): average knowledge growth **+22%**

This result indicates that the simulation environment has a positive effect on the rapid and effective acquisition of conceptual knowledge.

The results of the conceptual test showed that students in the experimental group mastered abstract optical phenomena such as light interference and diffraction faster and more deeply through visual modeling.

The dynamic visualization and ability to change parameters in the simulation environment helped students better understand the cause-and-effect relationships between events.

The results of the practical tasks showed that there was a significant difference between the groups

Control group (CG): high results were recorded, as students developed skills in working with real equipment, making measurements, and accounting for experimental errors;

Experimental group (EG): The level of practical skills was observed to be average, mainly limited to interactive activities in a virtual environment.

This result confirms the superiority of real laboratory training in the formation of psychomotor competencies. Likert scale questionnaire showed that the experimental group had a higher level of motivation. This was influenced by the following factors interactive visual environment, the ability to work with changing parameters in real time, student participation.

The results show that simulation technologies are an effective tool for increasing students' intrinsic motivation.

According to the results of the overall analysis , the highest pedagogical efficiency was observed in **the blended learning model** . That is:

Simulation lab + real lab experience = maximum learning efficiency allowed for a visual reinforcement of theoretical concepts and the development of practical skills in a real-world environment.

DISCUSSION

The results of this study show that simulation laboratories have high didactic effectiveness in teaching abstract and difficult-to-observe physical phenomena in the optics department. In particular, in the process of modeling light interference, diffraction, and wave properties, the simulation environment significantly reduces the cognitive load of students and enhances their visual-cognitive imagination.

This result is consistent with Mayer's multimedia learning theory and the concepts of Cognitive Load Theory, which states that visual and interactive elements facilitate the processing of complex information and ensure deep learning.

However, the research results also show that real-world laboratory exercises have an advantage in developing the following important competencies in students: **technical skills** — working with physical equipment, adjusting and controlling it, **experimental experience** - carrying out real measurements and recording the results. **A culture of scientific measurement** - taking into account errors, developing accuracy and methodological discipline. These aspects confirm the importance of a realistic laboratory environment in providing an authentic learning experience.

In this regard, the results of the study show that relying on only one teaching approach is not enough. The most optimal pedagogical model is **a blended learning model that integrates simulation and real laboratory approaches** . This model allows for the consolidation of theoretical knowledge in a visual and interactive environment and the development of practical skills in real conditions.

As a result, the blended approach serves to balance the development of not only cognitive, but also psychomotor and affective competencies in students .

CONCLUSION

The results of this study indicate that simulation and real laboratory experiments are important complementary didactic tools in optics education. Both approaches have their own pedagogical advantages and serve different learning objectives.

Simulation labs allow students to quickly master complex and abstract optical phenomena—interference, diffraction, and the wave properties of light—in a visual and interactive way. This enhances conceptual understanding and reduces cognitive load.

Real laboratory experiments are important in developing practical competencies in students, including skills in working with equipment, a culture of experimental measurement, and an approach to scientific research.

According to the results of the study , the highest pedagogical effectiveness is achieved through **a blended learning model that integrates simulation and real laboratory approaches** . This model provides an optimal balance between in-depth mastery of theoretical knowledge and strengthening of practical skills.

Therefore, combining these two approaches is recommended as the most scientifically and practically optimal solution in developing modern pedagogical strategies in optics education .

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