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Online Virtual Reality-Based vs. Face-to-Face Physics Laboratory: A Case Study in Distance Learning Science Curriculum

Irini Lakka *, Vasilis Zafeiropoulos and Antonios Leisos

School of Science and Technology, Hellenic Open University, 26335 Patras, Greece; vasiliszaf@eap.gr (V.Z.); leisos@eap.gr (A.L.)
* Correspondence: eirini.lakka@ac.eap.gr

Abstract: In the context of this work, a physics laboratory exercise was designed and implemented in a virtual reality environment with the aim of familiarizing students with the process of collecting measurements, applying basic methods of statistical analysis, and drawing conclusions. Two groups of second-year students from the "Natural Sciences" undergraduate program of the School of Science and Technology at the Hellenic Open University (HOU) were used to evaluate the effectiveness of the training methodology. The first group consisted of 31 students who performed the laboratory exercise in person with the guidance of a tutor, while the second group consisted of 26 students who used the virtual reality laboratory without supervision. The results showed that the second group demonstrated an improvement in achieving the expected results.

Keywords: virtual reality; virtual laboratories; physics education; distance education

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1. Introduction

Acquiring practical skills is crucial for gaining knowledge, and it is typically achieved through the experiences provided by the experimental process and laboratory exercises [1,2]. Physics heavily relies on observation and experimentation to establish the principles and fundamental laws governing the natural world. Science instruction without any experiment is hardly conceivable [3], and experiment is fundamental to scientific methods investigating nature. In science, experiments are used to prove certain hypotheses through deliberate observation. Experimentation is always closely linked with theoretical modeling, while the inquiry process is always based on an intimate interaction of experiment and theory [4]. This is why, in physics institutions, students actively engage in laboratory activities, where rules and insights are generated through systematic observations, investigations, and experiments [5]. The classic form of the implementation of laboratory training includes the student's physical presence in the laboratory area, and this is generally referred to as hands-on laboratories. Moreover, in hands-on laboratories, the equipment required to experiment is included apart from the person's physical presence.

Even though the experimental process has a primary role in enhancing learning, there are cases where many educational institutions cannot provide students with the necessary resources for conducting experiments (i.e., distance learning education programs). One of the main reasons is that every laboratory must have specialized equipment and workspace for training, which is a significant financial burden [6,7]. Moreover, for learning to be effective, students should be divided into small groups when performing the experiments, which necessitates increasing the number of teaching staff [2]. In addition, students must practice with a variety of hazardous materials (e.g., fire), which can increase the likelihood of accidents [1].

In another approach, virtual laboratories offer an adequate alternative option for situations in which physical presence in the laboratory area is not possible, the cost of its implementation is high, or there is high risk in the experimental procedure. Simulation labs or virtual labs mimic real experiments, they are computer-based simulations in which the user can operate the equipment in much the same way as if they were physically present in the lab [8–10]. The equipment required is not real but simulated on a computer, and the learners handle and interact with virtual materials, models, and experimental setups to observe and understand various phenomena. Consequently, virtual labs are more cost-effective than traditional laboratories since they require limited equipment, personnel, and operating costs.

Virtual laboratories can be excellent educational tools [11–17] that increase the knowledge and the motivation of the students while at the same time helping instructors better understand students' knowledge acquisition. In contrast to hands-on laboratories, the users focus on critical points of the experiment, while the same experiments can be repeated multiple times until students achieve their understanding and learning objectives. Additionally, students tend to prefer virtual labs since they are less likely to lead to measurement errors [18]. In traditional laboratories, students can find themselves amid complicated procedures. In contrast, when using virtual labs, they can instantly access data, enabling instructors to assess their understanding more effectively. Although it is important for students to encounter challenges and failures in the lab to develop problem-solving skills, these setbacks can sometimes obscure the intended learning outcomes [19].

The contribution of virtual laboratories to laboratory education was particularly recognized during the COVID-19 pandemic and the lockdown that followed, where many on-campus courses shifted to virtual laboratories, allowing students to have laboratory experience. In such situations, remote education technologies enhance learning if appropriate strategies and initiatives are followed [20–22]. Online education became popular and allowed students to use their time effectively, while virtual laboratories successfully contributed to the education of undergraduate and postgraduate students and allowed them to complete their laboratory classes without affecting the quality of learning [23–25].

In addition to hands-on labs and virtual reality labs, there are two more technologies employed in practical education: augmented reality labs and remote laboratories. Augmented reality labs combine virtual and real objects in a real environment, and students can exercise interactively in real time. They help students better understand, recall, concentrate, and interact, and they offer more attractive learning environments than hands-on laboratories [26,27]. In remote labs, access to lab equipment is achieved via the Internet. The experimenter remotely operates and controls the real equipment through an experimentation interface [28,29].

From the above discussion, it is evident that virtual reality, augmented reality, and remote labs are new trends in education as they offer many students the opportunity to experiment, which is not always possible with real labs. However, there is research demonstrating the fundamental role of traditional laboratory training. While distance learning is modern, convenient, and adequate, it cannot replace social contact with colleagues and teachers [30]. Hands-on laboratories give students the chance to manipulate the actual items of the experiments [31] and enhance students' skills in collecting scientific evidence in real conditions, i.e., with unavoidable measurement errors [32]. Furthermore, there is no doubt that not all the practices of a real laboratory can be reproduced through simulation in the virtual laboratory, while hands-on laboratories appear to enhance students' conceptual understanding more than virtual laboratories [33].

Some of the problems and drawbacks of virtual reality laboratories include their complex modeling and being resource-intensive. Students lack real experience that could make them more responsible and careful, and this justifies the view that virtual reality laboratories should only be used when a real laboratory is unavailable [34], or that the final stage in training should be by using real equipment, which can be only achieved through actual hands-on experience [35].

Although the constructivism approach emphasizes the value of students actively participating in their own education, it does not particularly advocate for physical manipulation [36]. Cognitivism emphasizes the necessity of active information processing and focuses on skill practice by students, but there is neither theoretical nor empirical evidence that advances the physical manipulation of materials as a prerequisite for active processing and practice [37]. However, research results indicate that, in some cases, virtual reality laboratories seem to be more effective in physics learning than hands-on laboratories [38]. In this study, students performed better on conceptual questions and developed a greater ability to manipulate real components when operating virtual laboratories. Conversely, only virtual laboratories give students the chance to manipulate conceptual objects that lack perceptual fidelity or represent and analyze phenomena of small dimensions, i.e., molecular dynamics and astronomy [39]. Virtual laboratories can provide representations that are just as equivalent to students as hands-on laboratories [40].

As a result, the combination of traditional and virtual experiments has shown to be more effective for learning than real or virtual experiments alone [41,42].

Virtual laboratories are widely used in physics education. They aim to improve students' science literacy in various areas, including the basic physics concept of material measurement [43], understanding of electromagnetic fields and magnetism concepts [44], fluid mechanics [45,46], rotational dynamics materials [47], thermodynamics [48], electricity [49], and the photoelectric effect [50]. According to [51], the need for virtual simulations that mimic real physical laboratories will only increase in the next few years. As traditional teaching advances toward using new technologies that foster computer-based technologies and remote operations, it is expected that virtual laboratories will play a major role not only in industrial training but also in academic training.

For instance, the Natural Sciences curriculum curriculum at the Hellenic Open University faces several challenges when providing laboratory education to its students. Due to the nature of the studies (distance learning), students' laboratory work is carried out in a limited time frame, and the students follow an intensive training program. This implies that students should be very well prepared for the laboratory exercise, which unfortunately is not always the case. For this reason, efforts have been made in recent years to develop virtual and remote laboratories for physics, chemistry, and biology. However, virtual laboratories with virtual reality technologies have only been developed for the Biology Lab. of HOU [52].

In this study, we focus on the impact of virtual laboratories on distance education with laboratory training while time and distance constraints exist. Our research aims to give the chance to the students to be better prepared for the hands-on laboratory, or to replace it when its implementation is impossible.

This paper presents a first attempt at using virtual reality technology in one physics laboratory exercise that is part of the obligatory "Physics Laboratory" course of the Natural Sciences program study. The paper is structured into two parts. The first part presents the methodology used, including the laboratory exercise chosen, the application developed, and the research methodology. In the second part, we present the results of the survey regarding the degree of achievement of the expected results and students' attitudes toward the methodology followed.

2. Materials and Methods

The laboratory exercise chosen for this study is the analysis of the motion of a simple pendulum, which is used to introduce to the students the main aspects of data analysis. In traditional face-to-face labs (FFL), students conduct this experiment by manually measuring the motion of a few physical pendulums and recording their data. For the virtual reality laboratory (VRL), a simulation application was developed using Unity 3D software (ver. 2021.3.25f1) that includes a realistic 3D environment of the Physics Laboratory of HOU along with ten different pendulums as in the real experiment. The user navigates into the virtual lab, measures the periods of the pendulums, and applies a statistical technique to extract physics results. For this purpose, the VRL also includes a stopwatch that allows students to record their data.

To compare the effectiveness of the VRL and FFL, a sample of students was divided into two groups: One group conducted the laboratory exercise using the VRL, while the other group used FFL. After completing the exercise, both groups were given a survey to evaluate their understanding and acquisition of basic knowledge of data analysis. The survey included anonymous questionnaires, and students' attitudes toward the followed methodology were also assessed.

The results of the survey will be discussed in the following sections.

2.1. The Laboratory Exercise

The laboratory exercise chosen for the present study was the first laboratory exercise of the Physics Laboratory course offered by the "Natural Sciences" undergraduate program of the School of Science and Technology at the HOU. The exercise involves the use of 10 different pendulums with different lengths and the measurement of their period of oscillation. To conduct the exercise, each pendulum is slightly deflected from the vertical position and allowed to move freely, while a timer is activated. Once the pendulum has completed several oscillations, the timer is stopped, and the reading is recorded on a table. Then, the mean value of the period as well as its error is evaluated by the student.

According to the theory of free oscillations, the period (T) and the length (L) of a pendulum are related as $T^2 = 4\pi^2 L/g$, where g is the constant acceleration of gravity. Even though this formula is an approximation, known as mathematical pendulum formula, it is very commonly used at least for small deflections of the pendulum. Since the period of oscillation is related to the length (L) of the pendulum with the simple relation $T^2 = aL + b$, where a and b are constants, the values of the pairs (L_i, T_i^2) for the ten pendulums should lay in a straight line. Consequently, parameter a can be used to determine the acceleration of gravity g, while b should be zero. Using the method of least squares, the slope a and its error Δa, as well as the constant b and its error Δb, are determined. Finally, the acceleration of gravity g and its error Δg are calculated using error propagation.

The use of different pendulums with different lengths enables students to observe and analyze the relationship between the oscillation period and pendulum length. Using the method of least squares, students also learn techniques for fitting the experimental data and estimating parameters as well as their errors. Finally, the experiment allows students to calculate the acceleration of gravity, which is an important physical constant in mechanics, while students can compare their experimental results with the theoretical value of the acceleration due to gravity and analyze any discrepancies. This provides an opportunity for them to reflect on the limitations and sources of error in their experiment.

2.2. The VR Application

The Onlabs-3.0 application, available at http://snf-858823.vm.okeanos.grnet.gr/onlabs/ (accessed on 30 June 2023), was utilized to implement the VRL. Onlabs was developed using the Unity 3D game engine and the C# programming language and provides a high level of realism to its users. There are three modes of operation: command mode, evaluation mode, and experiment mode. In the command mode, the user follows step-by-step instructions to conduct the experiment. In the evaluation mode, the user performs the experiment while simultaneously being evaluated. Finally, in the experiment mode, the user practices the experiment without instructions or evaluations. Figure 1 is a screenshot of the virtual environment for the laboratory exercise used in this work demonstrating the application's attention to detail and its ability to replicate the real physics lab environment.

To simulate the real motion of the simple pendulum, we used the equation of the damped oscillation as follows:

$$\theta = \theta_o e^{-t/\tau} cos(\omega t)$$

where θ_0 is the initial deflection angle, τ is a time constant analogous to the damping constant, and ω is the angular frequency ($\omega = 2\pi/T$) that depends on the deflection angle according to the following formula:

$$\omega = \sqrt{g/l}\frac{1}{1+\left(\frac{1}{2}\right)^2 sin^2\left(\frac{\theta_0}{2}\right) + \left(\frac{3}{8}\right)^2 sin^4\left(\frac{\theta_0}{2}\right) + \left(\frac{15}{48}\right)^2 sin^6\left(\frac{\theta_0}{2}\right)}$$

Figure 1. The virtual laboratory environment of the pendulum lab exercise. There are 10 pendulums of different lengths (8 are shown in this screenshot with blue color) that can be deflected to observe their motion.

To accurately simulate the motion of the pendulum, the time constant τ was estimated. The process of estimating the time constant τ involved several steps. First, the video of the real pendulum motion was captured and analyzed using the Tracker software (ver. 6.3.1) [53]. The Tracker software is a video analysis software that is used to analyze the motion of objects captured in video and to extract various kinematical variables, such as the position, speed, and acceleration of an object as a function of time. In our case, the software was used to record the deflection angle as a function of time for various pendulums with different lengths.

The simulation of the pendulum motion was performed using the mathematical equations that describe damped oscillations. The least squares method was applied to estimate the damping constant as the value that minimizes the difference between the simulated and actual pendulum motion. It must be emphasized that even though in the model used by the students, it is assumed that there is no friction, and consequently the motion of the pendulum is a simple harmonic motion, i.e., $\theta = \theta_0 \cos(\omega t)$, the simulation accurately mimics the real motion of the pendulum, with a constant τ different from zero.

2.3. Methodology

The laboratory course in question was designed for second-year students who had already taken compulsory theoretical courses in mechanics. In total, 57 students participated in the course, which is offered through distance learning. Prior to conducting the experiment, all students had in hand the laboratory guide along with video tutorials on the oscillation of the simple pendulum, the measurements they should perform, and data analysis. Then the students were divided into two groups, with each group conducting the experiment in a different laboratory environment.

The first group (Group A, number of students N_A = 31) conducted the experiment using a face-to-face laboratory (FFL) environment approximately six months after their theoretical training. The second group (Group B, number of students N_B = 26) conducted the experiment using the virtual laboratory environment (VRL) immediately after their theoretical training.

After the experiment was completed, all students were asked to anonymously complete a questionnaire with comprehension questions. The purpose of the questionnaire was to compare the two groups and assess the difference in the learning outcomes; additionally, students were asked to evaluate the entire laboratory exercise to determine their attitudes and feelings toward it. The overview of our methodology is depicted in Table 1.

Table 1. Overview of the methodology.

Theoretical Education about Oscillations (N= 57)	
Theoretical Distance Education about Simple Pendulum Oscillation (Textbook)	
Video Tutorial about Simple Pendulum Oscillation (Laboratory Guide)	
Experimental Education, Separation of 57 first-year students into two groups	
Experiment FFL (N_A = 31) (Duration: 4 h)	Experiment VRL (N_B = 26) (Duration: N/A)
Questionnaire	

3. Results

The first set of questions in the questionnaire aimed to evaluate the students' understanding of experimental procedures, scientific measurements, and data analysis. There were a total of eight questions, and each correct answer was awarded one point. The questions were designed to assess students' knowledge of basic concepts related to the experiment they had conducted, such as the procedure for measuring the period of oscillation of the pendulum, the methods for minimizing errors in measurements, and the use of statistical analysis to derive the values of physical parameters. The maximum score that a student could achieve on this set of questions was eight, indicating a comprehensive understanding of the experimental procedures and the associated concepts.

The Shapiro–Wilk test was conducted to check the normality of our data, which revealed that it did not follow a normal distribution. Therefore, we employed the nonparametric Mann–Whitney U test to identify any significant differences between the two groups. The results showed that the scores obtained by the VRL group were significantly higher than those obtained by the FFL group (U = 261, p = 0.023). This suggests that the VRL method was more effective in enhancing students' understanding and knowledge of the experimental procedures, scientific measurements, and data analysis than the traditional FFL method. Figure 2 shows the score frequency distribution for both samples, while Table 2 presents the mean score and associated error for each group.

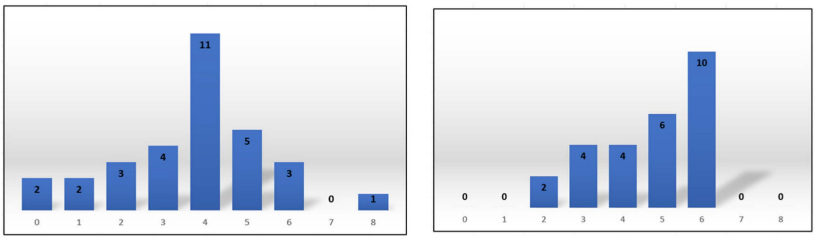

Figure 2. Score frequency distribution for FFL (**left**) and VRL (**right**). The horizontal axis values represent the score (number of correct answers), while the numbers at the top and inside the bars the number of students that achieved the corresponding score.

Table 2. Mean and statistical error on the mean of the scores between the two groups.

Group A (FFL)	Group B (VRL)
3.7 ± 0.32	4.7 ± 0.26

In addition, students were asked to answer evaluation questions about their experience. The score for each answer was given based on the degree of satisfaction using a Likert scale: 1 corresponds to the answer "not at all", 2 corresponds to the answer "a little", 3 corresponds to the answer "moderate", 4 corresponds to the answer "quite a lot", and 5 corresponds to the answer "very much". Also, in these cases, the Shapiro–Wilk test for normality showed that our data did not follow the normal distribution, and consequently, the nonparametric Mann–Whitney U statistic was used to identify statistically significant differences between the two groups. Table 3 shows the average score for each question in each group, as well as the *p*-value of the test.

Table 3. Mean scores on the evaluation questions for the two groups.

Group A (FFL)	Group B (VRL)
Q1: Could this laboratory exercise be successfully performed with only the laboratory guide, without guidance from the teacher?	
2.1 ± 0.17	3.8 ± 0.17
U = 18 $p < 0.001$ Statistically significant difference between the two groups	
Q2: Is the environment of the laboratory exercise satisfactory?	
4.7 ± 0.16	4.5 ± 0.14
$p = 0.38$ The two groups were not statistically significantly different.	
Q3: Is the timing of the laboratory exercise satisfactory?	
4.1 ± 0.22	4.1 ± 0.1
$p = 0.24$ The two groups were not statistically significantly different.	
Q4: Was the duration of the laboratory exercise sufficient to carry it out, draw conclusions, and achieve its objectives?	
4.5 ± 0.13	4.4 ± 0.1
$p = 0.37$ The two groups were not statistically significantly different.	
Q5: The instructions were clear and understandable in their content.	
4.7 ± 0.13	4.3 ± 0.16
$p = 0.08$ The two groups were not statistically significantly different.	
Q6: Was my prior knowledge sufficient for the laboratory exercise?	
3.7 ± 0.11	3.7 ± 0.18
$p = 0.72$ The two groups were not statistically significantly different	
Q7: I would repeat the laboratory exercise to refresh my knowledge.	
3.4 ± 0.21	4.1 ± 0.16
U = 145 $p = 0.03$ Statistically significant differences between the two groups	

The answers given by the students to the evaluation questions showed that there was a statistically significant difference between the two groups in terms of their ability to successfully perform the experiment without the guidance of a teacher. Specifically, the scores of those who performed VRL were higher than those who performed FFL. This indicates that with VRL, we provide a better learning environment for students to learn and perform the experiment.

In addition, the evaluation results showed that there was a statistically significant difference between the two groups in terms of their willingness to repeat the laboratory exercise and update their knowledge. The scores of those who performed VRL were higher, a result which was statistically significant. This suggests that the VRL had a more positive impact on the attitudes of the students toward the laboratory exercise, making them more willing to engage in further unsupervised learning.

In the other evaluation questions, there was no statistically significant difference between the responses of the two groups. This indicates that the laboratory environment, time, duration, instructions, and prior knowledge of the students did not significantly affect the assessment results. Therefore, we can conclude that VRL can be an alternative to simple traditional laboratory exercises and an effective way for students to become familiar with experimental procedures and scientific measurements.

4. Discussion

Based on the statistical analysis of the assessment questions, the VRL methodology (at least in this case, where simple experimental procedures are followed) had significant advantages over traditional laboratory teaching methods. The fact that the VRL was conducted immediately after the theoretical courses, as opposed to the FFL, which took place six months later, played a major role in the improved learning outcomes. However, it should be noted that this result should be considered in conjunction with the flexibility that VR affords. Students can engage in VRL training at their own convenience, free from time constraints and the associated pressure. They can revisit and repeat virtual experiments as many times as needed to master the subject matter, making the VRL methodology a more flexible and adaptable teaching method.

Even though the idea of replacing a hands-on experiment with a VR alternative may initially raise eyebrows, the core goal here is ensuring that students receive effective training, especially in the realm of distance education. A practical example of this concept is that by substituting a specific hands-on experiment with a corresponding VR simulation (which can be conducted outside the restricted laboratory course schedule), there is room to introduce an additional hands-on experiment into the laboratory course.

The students' responses to the evaluation questions were also indicative of the advantages of the VRL method. Students reported that they were able to successfully perform the experiment without the guidance of a teacher, relying only on the laboratory guide. This indicates that the VRL method provides students with a more independent and self-directed learning experience, which is particularly important in the context of distance education and lifelong learning.

The VRL method was found to be effective in refreshing students' knowledge, which is another key advantage. In the rapidly evolving field of science and technology, it is essential for students to continuously update their knowledge and skills. The VRL method can help students achieve this by providing them with an opportunity to revisit and reinforce their knowledge through laboratory exercises.

However, there is room for improvement in the VRL methodology. A future improvement could be the addition of a guidance function that allows students to formulate hypotheses and verify their results for self-assessment. This would further enhance their learning and understanding of the scientific method.

Finally, in an extension of this work, the VRL methodology could also be used in secondary education for teaching oscillation phenomena. The VRL can provide a simulated laboratory environment for pupils to familiarize themselves with the experimental process before conducting live experiments. This can enhance their understanding and confidence in performing experiments, leading to better learning outcomes.

5. Conclusions

For the needs of the present study, a virtual reality laboratory was designed and implemented in order to familiarize distance education students with the application of basic methods of statistical analysis. For the evaluation of our methodology, responses to questionnaires were collected from two groups of second-year students of the "Natural Sciences" undergraduate program of the School of Science and Technology at the Hellenic Open University. The students of the first group performed the laboratory exercise of simple pendulum oscillation, guided in person by a faculty advisor, while the students of the second group used the virtual reality laboratory without supervision. The students of the two groups then answered questionnaires aimed at evaluating the virtual reality laboratory in relation to the learning outcomes it offers, as well as the students' emotions and attitudes.

The results of this study suggest that virtual reality laboratories can be a valuable tool in teaching and learning in distance education programs. The use of the VRL led to statistically significant improvements in student performance on assessments compared with the traditional laboratory group. Additionally, students in the VRL group reported higher levels of satisfaction and confidence in their ability to conduct experiments without guidance from the teacher. These findings have important implications for the use of VRLs in secondary education as well, where they can be utilized to prepare students for live experimental processes and promote lifelong learning. A potential future improvement to the VRL could include the addition of a guidance, hypothesis formulation, and verification function for self-assessment by students, further enhancing their ability to conduct experiments independently.

In conclusion, this study underscores the significant advantages of the virtual reality laboratory (VRL) methodology, particularly when applied to distance education programs where time and geographical constraints come into play. The timing of VRL sessions, scheduled immediately after theoretical courses, proves instrumental in achieving improved learning outcomes. The flexibility offered by the VRL, along with the independence it cultivates, holds immense value, especially in the context of laboratory distance education, and the VRL methodology can play a vital role in refreshing students' knowledge, crucial in today's fast-paced scientific and technological landscape.

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