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# Επισκόπηση των εκπαιδευτικών προσεγγίσεων της χρήσης των εικονικών εργαστηρίων στην εκπαίδευση επιστημών και τεχνολογίας

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# Επισκόπηση των εκπαιδευτικών προσεγγίσεων της χρήσης των εικονικών εργαστηρίων στην εκπαίδευση επιστημών και τεχνολογίας

# Educational approaches concerning virtual laboratories usage in science and technology education: A review

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## Abstract

In science, technology and engineering education the new technological approaches (such as simulations, remote labs, virtual labs, virtual worlds) have not been fully adopted because on-site laboratory sessions are required for necessary skill acquisition. Virtual laboratories offer a supportive solution, specifically in distance education, where on-campus- laboratory time is limited. Thus, different educational approaches are used to explore usefulness of virtual labs. These include the pre-lab practice, the blended use and the stand-alone approach. The peer-reviewed literature was the main source of information and data about virtual laboratories used in science and technology education. Most studies suggested that a blended approach might offer the advantages of both methods.

**Keywords:** *Virtual laboratories, laboratories, educational approaches*

## Περίληψη

Οι νέες τεχνολογικές προσεγγίσεις δε χρησιμοποιούνται ευρέως στην εκπαίδευση των επιστημών, της τεχνολογίας και της μηχανικής, λόγω των απαραίτητων εργαστηριακών πειραμάτων. Τα εικονικά εργαστήρια προσφέρουν μια υποστηρικτική λύση, ειδικά στην εξ αποστάσεως εκπαίδευση, όπου ο εργαστηριακός χρόνος στους χώρους του πανεπιστημίου είναι περιορισμένος. Έτσι, χρησιμοποιούνται διαφορετικές εκπαιδευτικές προσεγγίσεις, ώστε να διερευνηθεί η χρησιμότητα που μπορούν να προσφέρουν τα εικονικά εργαστήρια. Αυτές περιλαμβάνουν τη χρήση εικονικών εργαστηρίων ως προ-εργαστηριακή πρακτική, τη συνδυασμένη χρήση εικονικών και φυσικών εργαστηρίων και τέλος την αυτόνομη προσέγγιση, όπου χρησιμοποιούνται μόνο εικονικά εργαστήρια. Το ενδιαφέρον εστιάζεται στη βιβλιογραφική επισκόπηση ερευνών που σχετίζονται με τη χρήση εικονικών εργαστηρίων στην εκπαίδευση επιστημών και τεχνολογίας και αφορά στις εκπαιδευτικές προσεγγίσεις που υιοθετούνται. Οι περισσότερες μελέτες πρότειναν ότι η συνδυασμένη χρήση (μεικτή προσέγγιση) φαίνεται να είναι προτιμότερη, καθώς θα μπορούσε να προσφέρει τα πλεονεκτήματα και των δύο προσεγγίσεων.

**Λέξεις-κλειδιά:** *Εικονικά εργαστήρια, εργαστήρια, εκπαιδευτικές προσεγγίσεις*

## 1. Introduction

New technologies transform the educational procedure, since they facilitate the placement of learner at the center of the learning environment. The characteristics of this transformation become beneficial when they are accompanied with changes in teacher practices (Vosniadou & Kollias, 2001). According to Potkonjak et al. (2016), the teaching of Science, Technology, and Engineering has been relatively slow to adopt the new technological approaches, particularly in distance education, since laboratory sessions are required. The laboratory use contributes to learners' necessary skills acquisition provided by the hands-on lab experience (Wang et al., 2014). According to Hofstein & Lunetta (2004), when students become experienced with the laboratory equipment usage, the learning experience is improved. Moreover, hands-on laboratories contribute to a more thorough understanding of essential aspects of science and technology education (Kumar et al., 2014). Although, hands-on laboratories provide experimentation with "real systems", they require maintenance staff, high cost equipment and materials (Gomes & Bogosyan, 2009). The main obstacle of the implementation of science education in distance education environment is the fact that laboratory experimentation is a central prerequisite part of the skill acquisition process (Potkonjak et al., 2016). Thus, one of the greatest challenges in science education is how to make science laboratories available online (de Jong et al., 2013).

Traditional laboratories can be enriched with, or completely replaced by remote laboratories and simulated laboratories (Ma & Nickerson, 2006). Virtual laboratories are simulations of process models used to abstractly describe the equipment of a physical laboratory and the experimental process carried out in that laboratory (Rossiter & Rossiter, 2016). Simulations, as part of the virtual laboratories, offer learners a variety of opportunities to explore physical or biological phenomena (Akpan, 2001). As stated in Karakasidis, (2013), virtual laboratories can nowadays be accessed and used at a distance, exploiting a rich availability of technological tools that are used in distance education. In a virtual laboratory environment, learners use the virtual experimentation interface in order to conduct experiments on a variety of, even unobservable, phenomena (i.e. electricity, thermodynamics) and draw conclusions about the properties of materials and the results of theory application (de Jong et al., 2013). Furthermore, virtual laboratories provide science teachers with educational tools, which facilitate learning by highlighting significant information and removing unnecessary detail and thus support the educational process (Trundle & Bell, 2010). Educators can adjust several characteristics of a simulation model, such as the materials or the time scale, in order to better clarify and cultivate insight in certain phenomena which would otherwise remain obscure (de Jong et al., 2013). Thus, learners, with the guidance of educators in an interactive simulation environment, select and change the simulation parameters to achieve the educational goals which have been set (Vogel et al., 2006). It is thus held, that the resultant learners' active participation and interaction stimulates their interest in science (Zervas, Fiskilis, & Sampson, 2014).

According to Feisel & Rosa (2005) and as also indicated by a recent review study (Wang, et al., 2014), the main uses of virtual laboratories are:

i. As pre-lab practice before the hands-on experiments in traditional laboratory
ii. As an alternative to physical lab experiments
iii. As a substitute in the case of dangerous, expensive or non-practical models or systems.

The main benefits of using virtual laboratories are (Gravier et al., 2008; Ma & Nickerson, 2006):

1. Cost reduction, as physical laboratories need expensive equipment and staff.
2. Increased availability, as virtual laboratories can be used from any place at any time.
3. Increased accessibility, as virtual laboratories can be accessed from people who might not be able to travel to physical laboratory premises.
4. Improved safety, as dangerous materials or sensitive equipment can be handled without (health or damage) hazards.

These important benefits are identified in other recent studies, in various science domains, confirming that virtual labs offer advantages in science and technology educational procedure (Brinson, 2015; Heradio et al., 2016; Jong et al., 2013).

According to Babateen (2011), virtual laboratories contribute to knowledge building and information processing, help learners' guidance and encouragement and reduce the learning time spent in traditional laboratory.

Although, simulators are used to a great extent in science education domain as virtual laboratories (Makransky et al., 2016), the practical skills, which are acquired in a physical laboratory, through experience and continuous practice, are difficult to be acquired by using a virtual laboratory for education. Hands-on laboratories help learners to acquire haptic skills and instrumentation consciousness, which virtual laboratories are very difficult to offer (Abdulwahed & Nagy, 2011). As stated in Zacharia & Olympiou (2011), the hands-on experience is considered as *sine-qua-non* in physics education.

From the educational point of view, an educational simulation environment provides the educator with the ability to build a custom model of the phenomena or the processes which describe the system under study, so that the learner will better understand the characteristics of the model through experimentation (Jonassen & Land, 2012). Furthermore, technology-enhanced simulation offers educators the ability to form an attractive and interactive learning environment so that learners become active participants in the educational process (Cook et al., 2013). As stated in Smetana & Bell (2012), computer simulations, can also support content-based instruction based on the students' active participation.

The learning approach most often used when virtual labs are adopted is inquiry learning. In inquiry learning the information is not presented to the learner, but it is gained from the experimentation and interaction with a phenomenon or an abstract representation of it (model) (de Jong, Sotiriou, & Gillet, 2014). Also, through simulation, learners explore hypothetical situations, interact with a simplified and specific version of a system or a process, practice tasks, solve problems and draw conclusions (Ramasundaram et al., 2005; van Berkum & de Jong, 1991). Additionally, simulations facilitate science education via visualization and interactivity (De Jong & Van Joolingen, 1998). Thus, since learners participate actively in the educational process, they become more responsible learners, which is a significant tenet of distance education, where the learner is, according to Keegan, (1980), responsible for "*initiating the learning process and, to a large extent, for maintaining it throughout*". Computer simulations can support inquiry-based learning practices, including the formulation of research questions, hypothesis formulation, data collection and theory understanding, by stimulating the learner's active engagement (Rutten, Van Joolingen, & Van Der Veen, 2012).

Different studies (Cook, 2014; Lee, 1999; McGaghie, et al., 2012), indicated that technology-enhanced simulation, compared with no simulation (hands-off), is associated with more positive effects during education, such as increased flexibility and students' active participation and interaction. According to Pyatt & Sims (2012), experiments can be conducted in an online learning environment consisted mainly of a virtual laboratory.

Physical labs enable the interaction between students and the lab equipment and materials, but in order to achieve their educational purposes, laboratories must be fully equipped, concerning materials, facilities and training staff. When these requirements cannot be completely met, virtual laboratories may offer a partial solution, especially in distance education.

The purpose of this study is to present a brief survey of studies concerning the various educational approaches in the use of virtual laboratories in science and technology domains. This presentation, gives the educators the opportunity to select the most appropriate educational approach for their educational level and institution.

## 2. Methodology and research tools

The peer-reviewed literature was the main source of information and data about virtual laboratories used in science education. The searches for peer-reviewed journal articles and dissertations were conducted using the Google Scholar search engine, Directory of Open Access Journals (DOAJ) and several databases, including ERIC (Educational Resources Information Center), SCOPUS, ISI Web of Science and INSPEC. The search terms were general, so as to include as many relevant studies as possible. Firstly, the papers' abstracts were identified as relevant to the search criteria and worthy of further study and afterwards, the full articles were accessed. Finally, the focus on the specific research papers has emerged through a critical analysis of their content, while through their brief presentation an attempt is made to highlight representative examples of different approaches of virtual laboratories usage in science education.

## 3. Educational approaches in virtual laboratories usage

From the reviewed publications it was concluded that virtual laboratories have been used in a variety of educational settings and different educational approaches were adopted. Virtual labs were mainly used as pre-lab practice sessions before the hands-on experiments in physical laboratory, as a complementary educational tool combined with the traditional teaching approaches (blended approach) and in some cases as the main educational approach when substituting hands-on laboratories. These findings are in accordance with a study by Feisel & Rosa, (2005).

### 3.1 Pre-lab approach

The success of the laboratory sessions depends on the preparation that learners has had before perform the experiments (Makransky et al., 2016). Cognitive load theory implies that it is important to connect cognitive resources with the relevant activity, in order to have better learning results (Chandler & Sweller, 1991). Thus, it is essential that learners know the basics of working in a laboratory environment, concerning the equipment, the materials and the experimental procedure. Moreover, in several cases the laboratory equipment may be destroyed by improper use, as learners don't have the necessary laboratory experience (Zafeiropoulos & Kalles, 2016). Usually, learners are prepared for the lab sessions by educators in a face-to face tutorial lesson, using laboratory's user guide as manual. As an alternative approach, virtual laboratories are used in order to prepare learners for the physical laboratory usage. As stated in a

review study (Wang et al., 2014), simulations were often used as preparatory tool for physical laboratories work, contributing in better learning outcomes and performance.
Virtual laboratories have been used as preparation tools in different educational settings in science and technology education.
In biology domain, virtual laboratories were used in various studies. In Makransky et al. (2016), virtual labs (vLABs) were used in an undergraduate biology course, where students had the opportunity to be prepared at home for the microbiology lab session. 189 students participated in the study and results revealed that students who used virtual lab as preparation tool had similar increase in knowledge, motivation and self-efficacy in microbiology field.
In a distance education institution (Hellenic Open University, Greece), virtual lab is used as a valuable supplement to traditional laboratory session (Zafeiropoulos & Kalles, 2016). Virtual lab (OnLabs), was used by learners to interact with equipment and perform experiments, before they conduct the experiments in «real» laboratory. 19 biology undergraduate students evaluated the virtual lab and stated that it was a user-friendly and really helpful tool (Zafeiropoulos, Kalles, Sgourou, & Kameas, 2014).
In a study by Noguez & Sucar (2006), virtual lab was used in an undergraduate mobile robotics course, where project oriented and collaborative learning were combined. During the first lessons of the course, students used the virtual laboratory to practice basic concepts in mechanics, kinematics, sensors, programming and control. Then students started constructing a robot based on their experience from virtual lab. 20 students evaluated the virtual lab and stated that it was useful tool in learning process.
In Physics domain, a study from Puspitasari et al. (2014), used as preparatory tool the simulation of polymeter, as pre-lab training for learners.
In chemistry domain, the pre-lab activity usually consists of a short lecture, at the beginning of the session, enabling students to collect information about a specific experimental procedure and the needed chemical substances (Limniou, Papadopoulos, & Whitehead, 2009). During the aforementioned study, virtual laboratory was used to improve students' preparation before practical session. The teaching approach used was inspired by cognitive load theory of learning and constructivism.
Dalgarno et al.(2009) employed a virtual laboratory environment as a preparation tool for chemistry students in distance education institution, before the on-campus laboratory sessions. Results indicated that virtual laboratory was a really helpful preparatory tool. More than half of students stated that virtual lab assisted them to identify and discover apparatuses and other laboratory equipment. However, students, as useful resources, ranked the laboratory manual and the pre-lab exercises in higher position.

### 3.2 Blended usage approach

The combined use of physical and virtual laboratories, can offer the advantages of both educational tools. Rivers & Vockell (1987), for example, indicated that biology high-school students, that used laboratory simulations with regular classroom and laboratory instruction, achieved the objectives of the biology class at least as well as the students using the conventional educational method. In another study in biology domain (Huppert et al., 2002), undergraduate students that used both traditional and virtual laboratories were more successful in a conceptual test, than students that only attended traditional laboratories.

Diwakar et al. (2015) found that both students and teachers were ready to use virtual labs in biotechnology courses as supplementary tools in blended/distance education, as they may be effective for complementing education methods and teaching material, particularly when access to campus-on laboratories is limited. A study in biochemical engineering field (Domingues et al., 2010), revealed that the great majority (93%) of the undergraduate students who used virtual labs as supportive tool found them of great usefulness. As stated by the authors, the virtual labs were not created to replace the hands-on experiments.

In a chemistry course for undergraduate engineering students, virtual labs were integrated with hands-on experiments (Ramos et al., 2016). The results indicated that this combination assisted in the performance improvement in hands-on laboratory and that could contribute to the improvement of student learning. Another study in chemistry field adopted the combinational use of virtual laboratory and traditional laboratory experiments (Martinez-Jiménez et al., 2003). The study concluded that the blended educational approach facilitated the reflective self-training of students, helped to eliminate the overcrowding problem in campus-on sessions and finally contributed to the effective use of time from educators, as they focused on explanation of theory, since less time was spent to laboratory instrument operation and experimental procedures. Liu et al. (2008), explored the impact of virtual laboratories usage in combination with the prior knowledge of students. Undergraduate students with different prior chemistry knowledge levels took part in the research and it was found that they used different approaches to problems solving. Those students that had a high level of prior knowledge used computer simulations as a supplementary tool to verify their theory understanding. On the other hand, students with low level of prior knowledge used computer simulations as the core tool to complete their tasks.

Engineering education on electrical circuits includes hands-on experiments in physical laboratories. Kollöffel & de Jong (2013) carried out a research involving secondary vocational engineering students, in order to compare the blended approach to the traditional approach. Thus, the hands-on laboratories were supplemented with inquiry learning in a virtual lab. The results showed that the students who used the blended approach scored significantly higher on conceptual understanding and complex problem solving. Another study (Abdulwahed & Nagy, 2013) in engineering domain, used the blended approach, involving hands-on and virtual lab, and remote lab additionally. The three modes contributed to the maximization of learning outcomes as well as students' motivation.

### 3.3 Stand-alone approach

Although virtual laboratories have many advantages and have become popular, traditional hands-on laboratories offer advantages that can not be ignored, such as manipulation of concrete materials (Zacharia & Olympiou, 2011). Many comparison studies report no significant difference between virtual and physical, hands-on laboratories. For example, Bonde et al. (2014) compared a gamified laboratory simulation with hands-on laboratory, in a biotechnology secondary and higher education. The results showed that simulated lab could significantly increase learning outcomes and motivation levels. When the gamified simulation lab is used in combination with physical lab the results were improved. In another study (Gibbons et al., 2004), virtual experiments were compared to the hands-on ones. Simulations contributed in time saving without affecting the learning outcomes, as they where measured by performance score in assessment. Additionally, in some cases, performance was improved when virtual labs were used.

In chemistry domain one of the initial studies (Cavin & Lagowski, 1978), where undergraduate students could use physical or virtual laboratories, indicated that the possibility of replacing specific experiments with virtual ones was supported. As stated, the virtual experiments could be a strongly supportive tool in chemistry education. In another study (Tüysüz, 2010) in chemistry field, secondary education students conducted virtual experiments. The results showed that virtual laboratory experiments had positive impact in students' achievement levels and motivation. Moreover, another study (Pyatt & Sims, 2012) that involved secondary education chemistry students, revealed that students showed a preference on virtual laboratory experiments. Concerning the inquiry-based application used in the aforementioned study, students preferred the virtual and online choices.

Wiesner & Lan (2004) explored the impact of computer-simulated experiments upon student learning in chemical engineering laboratories in undergraduate level. The results showed that student learning was not negatively affected by using computer-based experiments. Nevertheless, results indicated that a total replacement of physical labs would not be welcome.

A study involved elementary students (Triona & Klahr, 2003), used virtual materials and instruments instead of physical ones to conduct a physics experiment. Results revealed that virtual approach had equivalent effectiveness when compared with hands-on approach. Additionally, virtual approach captured the significant features of the instruction, making the physical interaction unnecessary in the specific learning context.

### 3.4 Brief presentation of different approaches and conclusions

In the following tables the studies are classified according to the educational approach that is used.

**Table 1:** Virtual laboratories as preparation tool for physical laboratory sessions

| Primary author (year of publication) | Topic | Conclusions |
|---|---|---|
| Makransky et al. (2016) | Biology | Students who used virtual lab as preparation tool had similar increase in knowledge, motivation and self-efficacy in microbiology field |
| (Zafeiropoulos et al., 2014) | Biology | Trainees found virtual lab as a user-friendly and really helpful tool |
| Noguez & Sucar (2006) | Mechanics | Virtual lab was useful tool in learning process |
| Puspitasari et al. (2014), | Physics | - |
| Limniou et al. (2009) | Chemistry | Virtual lab was a helpful preparatory tool that assisted students to identify and discover instruments and other laboratory equipment |
| Dalgarno et al. (2009) | Chemistry | Virtual laboratory was really useful, as a helpful preparatory tool that supported instruments and other laboratory equipment discovery |

**Table 2:** Integrating virtual laboratories with regular classroom and physical laboratory instruction (blended approach)

| Primary author (year of publication) | Topic | Conclusions |
|---|---|---|
| Rivers & Vockell (1987) | Biology | Students used the simulations, achieved the objectives of the biology class at least as well as the students that used the conventional educational approach |
| Huppert et al. (2002) | Biology | Through simulation, students repeated the experiments, designed their self-paced studying and were prepared for the final examination |
| Diwakar et al. (2011) | Biotechnology | Students and teachers were ready to use virtual labs in biotechnology courses as supplementary tools in blended/distance education |
| Domingues Rocha et al. (2010) | Biochemical engineering | The great majority (93%) of the undergraduate students who used virtual labs as supportive tool found them of great usefulness |
| Ramos et al. (2016) | Chemistry | The combined use assisted in the performance improvement in hands-on laboratory and could contribute to the improvement of student learning. |
| Martinez-Jiménez et al. (2003) | Chemistry | The blended educational approach facilitated the students' self-training and helped to eliminate the overcrowding problem in campus-on sessions |
| Liu et al. (2008) | Electrochemistry | Students with different prior chemistry knowledge levels used computer simulations in different approaches to problems solving |
| Kollöffel & de Jong (2013) | Engineering | Students who used the blended approach scored significantly higher on conceptual understanding and complex problem solving |
| Abdulwahed & Nagy (2013) | Engineering | Blended approach contributed to the maximization of learning outcomes as well as students' motivation |

**Table 3:** Virtual lab vs. traditional teaching

| Primary author (year of publication) | Topic | Conclusions |
|---|---|---|
| Bonde et al. (2014) | Biotechnology | Simulated lab could significantly increase learning outcomes and motivation levels |
| Gibbons et al. (2004) | Biology | Simulations contributed in time saving without affecting the learning outcomes and in some cases, performance was improved |
| Cavin & Lagowski (1978) | Chemistry | Students in the simulation groups scored similarly or better than students in traditional laboratory groups |
| Tüysüz (2010) | Chemistry | Students who used the virtual laboratory increased their achievement level and improved their attitude towards chemistry |
| Pyatt & Sims (2012) | Chemistry | Students indicated a preference on virtual laboratory |

| | | |
|---|---|---|
| | | experiments |
| Wiesner & Lan (2004) | Chemical engineering | Student learning was not negatively affected by using computer-based experiments |
| Triona & Klahr (2003) | Science | Virtual approach had equivalent effectiveness when compared with hands-on approach |

The number of participants range from 19 to 400 and in one research apart from the students 100 teachers participated. In four studies virtual labs were used in sequential school years.

In studies where virtual labs were used as preparatory tool (Table 1), learners found this use really helpful. More than half of the studies used the blended learning method (Table 2) where virtual laboratories, as another tool inside the educational process, were combined with the physical lab sessions. Even, studies that used virtual labs in contrast with physical ones (Table 3) suggested that the blended approach could offer the advantages of both methods. In many studies, virtual labs are exploited in inquiry learning environment where experiments play a key role.

## 4. Conclusions and further research

Physical and virtual labs can be used in order to achieve similar objectives in science learning (Jong et al., 2013). According to Ma & Nickerson (2006) traditional laboratories can be supplemented with remote and simulated labs. Crucial part of laboratory success is the instruction design by the educators. Particularly, according to Alfieri et al. (2011), laboratories guidance should be carefully designed, so that students benefit from laboratories. Moreover, designers of virtual laboratories can make them attractive by highlighting significant information (Trundle & Bell, 2010) or modify simulation model characteristics, such as time scale, so that specific phenomena can be comprehended (Ford & McCormack, 2000).

The current review presents different studies in the science and engineering domains, where virtual laboratories were used in different educational approaches. Results of the aforementioned studies showed that when virtual labs are used as preparation tools before the physical sessions, students were benefited and participated actively in physical labs that followed. However, most of the reviewed studies suggested that virtual laboratories should not substitute physical ones and their advantages are better disclosed when combined with the traditional hands-on sessions (blended approach).

There is an improvement in effectiveness of simulations over the past decade, since technological advancements and improvements of instructional support are changing (Rutten et al., 2012).

The increasing number of virtual laboratories makes the literature review useful in order to comprehend and map the spectrum of simulators available for educational purposes in the specific domains. Moreover, the different educational approaches can be evaluated by educators and used according to their educational environments. Subsequently, we plan to develop an application to select through a personalized search the appropriate simulator, based on the educational needs of trainees and the educational approach selected by the educator.

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