REVIEW OF VIRTUAL LABS AS THE EMERGING TECHNOLOGIES FOR TEACHING STEM SUBJECTS

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Abstract

Laboratory experience is a key factor in technical and scientific education, but traditional laboratories are costly to maintain, limiting possibilities for practical exercises. Virtual laboratories have been proposed to reduce cost and simplify maintenance of lab facilities, while offering students a safe environment to build up experience and enthusiasm for STEM (Science, Technologies, Engineering and Maths) subjects without geographical limitations. Virtual labs enable students to participate and interact in inquiry-based classes where they can implement and analyse their own experiments, learn by using virtual objects and apparatus. Utilising virtual labs provides students with the chance to develop critical thinking, innovative and team working skills, all of which are highly valued in today's job market. Numerous virtual labs have been developed by different organisations and large-scale international projects, and many of these are available as open source software.

NEWTON project, as a part of European Union's Horizon 2020 Research and Innovation programme, is currently developing virtual labs to revolutionise the way STEM subjects are taught throughout European schools and colleges. NEWTON draws from the expertise of 14 European academic and industry partners and incorporates virtual reality with gamification and augmented reality with personalised learning. NEWTON has a special emphasis on developing virtual labs that are tailored to the needs of disabled students, such as deaf students and those with upper-limb disabilities. Here, we give a review of current virtual labs and discuss how NEWTON can overcome the existing limitations.

Keywords: Virtual labs, personalised learning, review, STEM education

1 INTRODUCTION

Experience in the laboratory and exercising scientific skills are key factors in science education, to empower the future scientists with a skillset that fills the needs of the scientific community [1], [2]. It is important that laboratory practises give students the confidence to deal with real issues in realistic environments. Furthermore, we need to engage students to build up motivation and enthusiasm for STEM subjects through large-scale initiatives to ensure enough graduates to meet the employment market's needs [2]. The number of graduates from science degrees in Europe has decreased in recent years, and the gender imbalance very much exists, despite efforts to encourage more girls to study science and engineering. However, to provide students with the chance of practising scientific skills requires enormous investment in time, funding and resources, which are always limited.

Online labs are science labs offered on computers and smart devices. Modern developments have enabled the inclusion of gamification, virtual worlds and augmented reality into virtual labs, bringing the user experience to a new dimension. New research which focuses on the sense of touch, via tactile feedback [3], [4], and olfaction [5] as important features in the students' learning experience assist in bridging the gap between real labs and virtual labs.

Virtual labs ease the pressure brought on universities and schools by cost and maintenance of real labs, while utilising the extensive technological knowledge of students today. At their best, properly planned and executed virtual labs have been found to increase students' knowledge, skills and performance in examinations, while reducing limitations by geography, health and safety, cost and availability [6]. In an online lab, investigation material, physical or virtual, is manipulated, and the effects of this manipulation are observed in order to gain insight into the relationship between variables in the conceptual model underlying the online lab.

Many virtual labs are already widely in use, but they are often perceived as mere additions to traditional lab set-ups. They have, however, potential to provide an equal, and often even enhanced, learning experience to the students, with many benefits that traditional labs cannot offer. Furthermore, disabled students benefit greatly from virtual labs as they remove all physical limitations of a traditional lab.

This paper is constructed as follows: in the first section, we give an overview of the advantages and challenges of virtual labs, and how to overcome the latter; in the second section, we present a review of the existing virtual labs and past evaluations of the same; the final section concludes the paper.

1.1 Advantages of virtual labs

Virtual labs offer a solution to the limitations of traditional practical classes in STEM education [7], by offering environments for students to interact with each other and use virtual objects and apparatus, through software interface which is connected to a hardware in one centralised place [1], [8]. Since elementary education reforms have emphasised inquiry-based learning, using virtual labs allow students to develop their reasoning, critical thinking, innovative and creative skills without the usual limitations of time, resources and space [9]. They also enable inquiry-based learning while assisting in the acquisition of deep conceptual domain knowledge and inquiry skills [2].

Virtual labs allow resources to be shared between geographically distributed educational institutions and users [1]. Virtual labs are easy to set up, use and maintain, with notable reductions in cost and time. Hardware labs on the other hand are difficult to set up and very time-consuming and costly for the institutions to manage, and require a lot of technical expertise to run [1]. In addition to being cheaper than hardware labs, virtual labs have the potential to be used in experiments that would be too dangerous or impossible to carry out in real life, e.g. practising surgeries or testing the functions of a nuclear reactor: these labs allow students to learn from mistakes without causing any real damage to themselves or others [7]. Experiments can also be repeated multiple times, providing students with the chance to change the parameters of their experiment [7], [8]. With regards to ethical education, the general view has largely changed in the past two decades, for example dissection labs becoming increasingly rare [6]. Virtual labs are a way to bypass these types of ethically questionable practices while teaching students about anatomy, physiology and biology. Similarly, medical students can practise surgeries with no risk to the virtual patient.

1.2 Challenges faced by virtual labs

Virtual labs have the potential to revolutionise the teaching of STEM subjects, but gaps in its recognised potential and the actual applications still exist. Virtual labs have become under criticism from their lack of real-life feel and not teaching about health and safety to students. With augmented reality, sensorial devices, live videos, interactive videos and serious games, students can immerse into an incredibly life-like lab experience while maintaining all the benefits of a virtual lab [9]. The use of avatars, as discussed in the next section, has also given virtual labs a new level of personalisation that allows students to feel more comfortable to interact with other users and carry out experiments themselves.

If the virtual lab is not designed and implemented correctly, possible over-simplifying and disregarding health and safety in the lab environment can become of concern [1], [8]. The health and safety education is particularly important in secondary level and during first year of higher level education, as this sets the ground for any future lab work the students might take part in. This first challenge has been overcome with the implementation of augmented reality and multisensorial learning [8]. The concern over health and safety can be tackled with emphasised safety education.

Virtual labs also generate data which relies on the underlying assumptions, thus lacking the level of natural variation, and therefore students do not become familiar with poor or uncharacteristic data, nor will they learn how to deal with issues rising from these types of data [6]. Students have raised concerns with not being able to handle real equipment, and feeling as if they are losing out on some stages of practical training available in traditional labs. However, even though in some cases handling real apparatus would be beneficial, such as in chemical and biomedical studies, virtual labs offer students the opportunity to make mistakes without real cost or danger. Virtual experiments give students multiple attempts, before moving onto a hardware lab at a further stage of their studies, if they choose to pursue a certain subject [6].

From the technological point of view, the incorporation of virtual labs into the education process often requires adjustment or extension of existing resources that are available within the labs. This is particularly difficult for teachers as they are required to at least understand the underlying technology behind virtual labs to be able to input new content, which is usually created and implemented by highly skilled programmers and graphic designers, who, in turn, need to cooperate with experts on respective subjects to realistically model virtual objects with their properties.

One of the hottest trends in modern learning is personalisation and adaptation: these are key features to be implemented in the NEWTON virtual labs. Today's learners expect education to be cater for a variety of learning methods, as one size does not fit all [10]. The fast-growing market for adaptive learning software is expected to reach $2 Billion in the Americas alone [11]. However, personalisation and adaptation are currently lacking in the clear majority of existing virtual labs.

2 EXISTING VIRTUAL LABS

2.1 Review of existing virtual labs

Numerous virtual labs have been developed by different organizations, and many of these are available as open source software. Students appreciate the instant feedback, flexible access, and repeatability of the experiments. Moreover, they are granted access to cutting-edge technology that might not otherwise be available.

The European Commission, who also fund the on-going NEWTON project, have funded several large-scale projects aimed at creating virtual labs and bringing them into main stream education. Few examples from recent years include The Go-Lab Project [12], which resulted in providing access to online science laboratories to European pupils aged 10 to 18. Educators can create their own labs and share these with other users, thus building on the existing resource network. Another EC funded project is the Library of Labs [13], LiLa, where the partners developed a portal with the result of mutual exchange of and access to virtual and remote laboratories. The features also include a tutoring system, and 3D-environment for online collaboration. Project VccSSe [14] provided virtual labs and training in physical laws, including simulation-based exercises. The aim of the project was to help the target group, 180 primary and secondary Science teachers to create their own learning objectives, and incorporating virtual experiments in these.

GridLabUPM [15] was developed in 2010 as a result of the Educational Innovation Project. The virtual laboratories in the Technical University of Madrid offer students practical experience in the fields of electronics, chemistry, physics and topography. The university emphasises practical experience as a key skill for any graduate, but many are nearly impossible to organise in real life due to their dangerousness, duration or the difficulty of managing the developed processes. Thus, virtual labs have been developed to overcome this problem. The platform, which is built on open source software OpenSim, hosts several virtual laboratories, where users can make real teaching practices [15].

Several virtual lab collections are subject-specific. For example, ChemCollective [16] is a collection of virtual labs, scenario-based learning activities, tutorials and concept tests for Chemistry. Teachers can use this content for their own laboratories, for alternatives to textbook homework, and for individual or team-based in-class activities. Furthermore, these virtual labs offer online simulations of chemistry labs designed to allow learners to select from hundreds of standard reagents (aqueous) and manipulate them as within a real lab, but without the added cost of real equipment and potential hazards.

Similarly, Random [17] is a web portal providing a set of web-based resources for students and teachers about probability, mathematical statistics and stochastic processes. Open Source Physics [18] consists of hundreds of open source virtual labs and provides curriculum resources that engage students in physics, computation, and computer modelling. For basic lab techniques and practical analysis exercises such as testing for Corn Mould, Gram Staining and Controlling Water Activity in Food, there is Nmsu Virtual Labs [19].

One of the primary objectives of developing virtual labs is to enable inquiry-based learning by students themselves, and many existing virtual labs offer this as a key feature. Through the virtual experiments of the TriLab [20] project students gain experience in the principles of control engineering, such as the main components and instruments of a feedback loop, the concept of open-loop control, feedback control, PID (Proportional-Integral-Derivative) control, and PID tuning. The virtual labs offer a combination of hands-on, virtual and remote labs in one software package by using LabVIEW.

Another central feature of virtual labs is interaction, transforming the student from a passive listener to an active participant in the learning process. The virtual labs offered by BioInteractive [21] are fully interactive simulations in which students perform experiments, collect data and answer questions to assess their own understanding and knowledge. The labs are a combination of animations, illustrations and videos to convey key information and engage students in the process of science. Similarly, the Ironmaking Virtual Lab [22], which utilises VSM (Visual Simulation Model) software, includes an interactive interface.

Many educators who might favour traditional labs to virtual labs still recognise their potential in complementing the often-limited traditional exercise possibilities. For example, Virtual CVD Learning Platform [23], was designed primarily to enhance certain elements of the hardware lab in the curriculum. It includes a 3-D graphical user interface, an instructor Web interface with integrated assessment tools, and a database server.

Students and educators alike have reportedly found the instant feedback provided by virtual labs notably rewarding. This reduces the workload for educators while motivating students. In one such virtual lab, the Virtual Electric Machine Laboratory [24], students can change any parameters, immediately observe the effects in the visually presented results and receive feedback on their experiments with electrical machinery. Furthermore, reducing the administrative burden related to lab sessions was one of the main goals in the development of eBiolabs [25], a platform that supports laboratory-based learning for different topics within biological sciences.

Due to the developments in technology and huge popularity of computer games, elements of gamification have successfully been introduced to virtual labs. Avatars have become increasingly popular, one of the best-known examples of which is Second Life [26], a 3D simulation of the real world. Several educational environments are built within Second Life, for example the Virtual Engineering Sciences Learning Lab (VESLL) [27] which guides students through a series of key quantitative skills and concepts. VESLL also provides interactive learning activities, multimedia displays, and instant feedback to students [27].

Similarly, Mechanisms and Machine Dynamics [28] module also includes a game-based lab environment, where students learn by interacting in virtual environments, such as Second Life, The Sims or World of Warcraft. This virtual lab introduces the principles of kinematics and dynamics and applies them to linkages, cam systems, gear trains, belt and train drives, couplings, and vibrations.

Accessibility, resulting in the removal of time and space-limitations, is one the greatest benefits of virtual labs. In some, students can practise offline as well as online, thus enabling learning at any time of the day. Virtual Labs in the CSU [29] are virtual labs developed for STEM subjects, and they are available from different sources like PhET Labs, Smart Science Online Science Labs, Free Simulations in MERLOT. To ensure fair access to all users, the software must also be compatible with a variety of devices. Gizmos [30] is a virtual lab which provides interactive simulations that allow students to learn Math and Science concepts. All Gizmos simulations are based on the latest national educational standards and compatible with many devices (including PC, Macs, iPads and Android). Lack of compatibility can greatly reduce the usefulness of otherwise a well-designed virtual lab.

In Table 1, existing virtual labs are reviewed. This table summarises the activities and learning materials available for the user (chat, email, video, interactions with avatars etc.), personalisation and adaptation elements, and whether the virtual lab is designed to accommodate a specific disability. Most of these virtual labs are designed for higher education rather than secondary level, and hardly any consider the needs of special education students. Even fewer incorporate personalisation or adaptation in their design. NEWTON virtual labs will be designed primarily for secondary level, though some are applicable for higher education, and personalised and adaptive learning will be incorporated into the exercises.

Table 1. Review of existing virtual labs. Level refers to secondary (SE), higher (HE) or adult education (AE).

Virtual lab name	Activities and learning materials	Level	Personalisation and adaptation	Disability	Refs
The Go-Lab Project	Multimedia material, inquiry-based learning activities	SE	Gamification	N/A	[12]
Library of Labs	Scheduling & tutoring system, library resources, 3D environment	HE	N/A	N/A	[13]
GridLabUPM	Simulation-based exercises	HE	N/A	N/A	[15]
Nmsu Virtual Labs	Animated simulations, discussion guides	HE	N/A	N/A	[19]
ChemCollective	Interactive learning activities, tutorials	HE	N/A	N/A	[16]
Random	Simulation exercises, online tutorials	HE	N/A	N/A	[17]
Open Source Physics	Chat, email, virtual reality	SE, HE	N/A	N/A	[18]
Project VccSSe	Virtual experiments, simulation-based exercises	SE	Project actively promoted inclusion and different learning styles.	Some proposals to develop virtual labs for disabled pupils. Disability not specified	[14]
BioInteractive	Virtual reality, video	SE, HE	N/A	Autism, emotional disturbance, learning disabilities, speech or language impairment	[21]
Ironmaking Virtual Lab	Interactive interface, teamwork	HE	N/A	N/A	[22]
Virtual CVD Learning Platform	3-D user interface, an instructor Web interface with integrated assessment tools	HE	N/A	N/A	[23]
Virtual Electric Machine Laboratory	Virtual experiments	HE	N/A	N/A	[24]
eBiolabs	Interactive animations and videos, quizzes, post-lab online assignments.	HE	Personalisation as part of the features. Not specified.	N/A	[25]
Second Life	Avatars interaction	SE, HE	Gamification	Learning disabilities, blind students, cognitive disorders	[26]
Virtual Engineering Sciences Learning Lab (VESLL)	Interactive learning activities, multimedia displays	HE	N/A	N/A	[27]
Mechanisms and Machine Dynamics	Virtual world, avatars	HE	Gamification	N/A	[28]
Virtual Labs in the CSU	Interactive objects, video and audio tutorials, offline access.	HE	N/A	Vision, hearing, mobility impairments, learning disabilities, ADHD, neurological	[29]

				and psychiatric disabilities	
Gizmos	Interactive simulations	SE, HE	N/A	N/A	[30]

2.2 Assessment of the effectiveness of virtual labs

It is important not to get carried away with all the newest developments in technology without considering whether virtual labs truly benefit the students' learning. Several studies have been carried out attempting to evaluate specific virtual labs (Table 2). De la Torre et al. [31] carried out an observational study on 197 Physics students and did report a positive correlation between the students' exam results and exercises in the virtual lab, where activities included chat, email and virtual reality. However, since there was no control group, such as a group of students who took the same exam but did not attend a virtual lab, it remains unclear whether this virtual lab really enhanced the students' learning or not.

Other studies, where control groups have been used, have found mixed results when comparing virtual labs to traditional labs. For example, Crandall et al. [32] reported no differences between the virtual lab test group and traditional lab control group in their assessment of Food Science students' learning. In this study, the sample size was rather small, a total of 48 students. On a larger study with 8432 participants, Merchant et al. [33], found contrasting results: virtual labs did improve students' learning outcome gains. Especially gamification factors, when students were playing alone as opposed to in a group, were found to have a more positive effect on learning than simulations and virtual worlds. Barrett et al. [34] measured both accuracy and efficiency of learning in a Chemistry lab, and while there was no difference in the accuracy of students' results between virtual and real labs, virtual models provided greater efficiency.

Cheng et al. [35] also studied gamification as a method of teaching evolution to 62 students, and they also reported a positive effect on the long-term knowledge retention of the students. While these studies provide evidence that virtual reality and gamification often improve learning outcomes, the fast-moving developments in technology such as augmented reality where students can experience the virtual world almost as the real world, have shown even greater potential. Lindgren et al. [36] found that when students learned about gravity and planetary motion in a whole-body interactive simulation, there were significant learning gains, higher levels of engagement and overall more positive attitudes towards science. Another method for multisensorial learning is to utilise haptic feedback, which has been found to increase the learning effectiveness of a virtual lab to the extent that the test group outperforms the control group [37].

NEWTON virtual labs are designed to include virtual reality, augmented reality, gamification aspects and multisensorial activities, to ensure they accommodate all learning styles. Previous evaluation frameworks for personalised technology-enhanced learning systems have largely focused on solely objectively evaluating the prediction power of algorithms, or alternatively subjectively evaluating the user experience, while not considering evaluation as a complex process including subjective and objective measures of learning effectiveness, learning efficiency, system accuracy, satisfaction, ease of use and learner engagement [38].

Virtual labs have reportedly been hugely beneficial in special education, which is one the key focuses of NEWTON. Baladoh et al. [39] where video with sign language, chat, email and virtual reality improved hearing impaired students' learning. Similarly, Passig and Eden [40] found that rotating 3D models had a significant impact on the learning of deaf students, bringing the gap between hearing impaired and hearing students in the post-test. Forbes et al. [41] studied the use of avatars in adult special education with autistic people, and found that the participants reacted to the avatar very similarly than they would in a real-life educational situation.

Table 2 presents a summary of existing studies on virtual labs. Most of these studies, as most virtual labs in general, focused on higher education; only one concerns adult education, and a few focused on secondary level virtual labs. Listed in this table are the types of technology (virtual reality, augmented reality, use of avatars, gamification) available for users, along with the method of assessment (objective, subjective or both), number of participants and results of the study.

Table 2. Studies on existing virtual labs. Level refers to secondary (SE), higher (HE) or adult education (AE).

Virtual lab name	Technology type	Level	Assessment methodology	Test group	Results	Ref.
Open Source Physics	Virtual reality	SE, HE	Objective: no control group	197 students	Positive correlation between exam results and virtual lab activities.	[31]
Virtual Lab for Electronic Circuits VLEC	Video (sign language), virtual reality	HE	Subjective analysis: objective pre- and post-tests	All Electronics students 2013-14	Improvement in hearing-impaired students' practical skills.	[39]
Forensic food science virtual laboratories	Virtual reality	HE	Subjective questionnaire; objective post-test	48 students	No difference between virtual and wet lab learning outcomes.	[32]
MotionBuilder, Vizard	Virtual reality, avatar	AE	Subjective questionnaire; objective statistical analysis	50 adults	Autistic participants expressed reduced mimicry of avatars, like that in real-life social situations.	[41]
Several	Virtual reality, gamification	SE, HE	Subjective meta-analysis	8432 students	Improvements in learning outcome gains. Games showed higher learning gains than simulations and virtual worlds.	[33]
Virtual Age	Virtual reality, gamification	SE	Objective (ANOVA, cluster analysis)	62 students	Positive effect on long-term knowledge retention.	[35]
MEteor	Augmented reality, simulation	SE	Subjective questionnaire; objective post-test	113 students	Significant learning gains, higher levels of engagement, and more positive attitudes towards science.	[36]
3D virtual lab	3D virtual reality, gamification	SE	Objective pre- and post-tests; subjective analysis	60 students (deaf and hearing)	Rotating 3D models improved the results for deaf students to the same level as hearing students.	[40]
Interactive virtual control laboratory (IVCL)	Virtual reality, haptic feedback	HE	Subjective questionnaire; objective pre- and post-tests	30	Test group outperformed control group in the post-test.	[37]
Organic chemistry laboratory	Virtual reality, 3D haptic interface	HE	Subjective questionnaire; objective post-test	41	No difference in accuracy of virtual and real models; greater efficiency for virtual models	[34]

3 USERS' PERCEPTIONS OF VIRTUAL LABS

Students report that they enjoy the instant feedback, flexible access and repeatability of the exercises that virtual labs have to offer. This reinforces the positive attitude most students have on virtual labs. Based on student feedback, they find themselves more focused on the learning rather than the risk factors of traditional labs, which helps them to perform better. Moreover, virtual labs enable experiments than would otherwise be too dangerous, such as studying the functions of a nuclear reactor. Moreover, the knowledge that in the virtual lab nothing harmful can happen makes students feel more relaxed and focused on the experiment at hand. Furthermore, the repetitive prompts make students feel more comfortable and confident in their exercise, further increasing their skillset [8]. In virtual labs where objects are tangible, students also learn quicker than when interacting with non-tangible objects [4]. Similarly, educators also benefit from the automatic marking and overall reduced administrative workload that comes with utilising technology. Virtual worlds offer science educators an interesting platform for faculty, and the opportunity to share resources and keep all records in one place.

When the user's action is limited to sitting at the laptop and moving the cursor around the computer screen, the user experience will never compare to the being physically able to move around the lab and feel the apparatus around. Interacting with physical objects through a tool lacks kinesthetic sensations that form the user's haptic impression of the object [3]. However, recent developments in virtual reality technology, such as virtual reality headsets, haptic surfaces (gloves and vests) and olfactory devices have revolutionised the way virtual labs can be taught. Culbertson and Kuchenbecker [3] evaluated the realism of haptic surfaces (surface friction, tapping transients, and texture vibrations) based on the subjects' perception of the haptic surface and the real surface it was modelled on. They found that the inclusion of these three qualities was dependent on the intensity of the real surface's property: slipperiness, hardness, or roughness. The consideration of these properties is important to create as life-like an experiment as possible for the user, thus also improving the learning experience for the students in the virtual lab. Overall, with the continuously developing technologies, there is truly no limit to what can be achieved in virtual labs.

4 CONCLUSIONS

Virtual labs have the potential to provide all students with practical experience in STEM subjects, while reducing the costs and minimising the hazards associated with real labs. Ethical issues in biology and medicine, for example, have been abolished thanks to virtual labs. Furthermore, virtual labs are not tied to geographical locations or time-limitations, and resources can be shared online between different organisations and institutions, as has been done because of many an international project. These existing collections of virtual labs are still being built on and expanded, and many thousands of students continue to benefit from them.

While there have been concerns regarding the effectiveness and realism of virtual labs, recent research has provided us with the tools to overcome these challenges. Augmented reality and the consideration of senses other than sight and hearing in the development process has helped bridge the gap between real labs and virtual labs, thus removing the issue of lack realism. Several studies have shown the positive impact of virtual and augmented reality, gamification and virtual worlds on students' learning, and all of these will be incorporated into the NEWTON virtual labs.

One of the key goals of NEWTON project is to create virtual labs with personalisation and adaptation, as this is the fastest growing software market in modern STEM education, and currently missing in most virtual labs. Most of the existing virtual labs are also aimed at higher education, even though the disconnection by students from STEM subjects should ideally be tackled at the secondary level. NEWTON pilot schools are a combination of both higher and secondary educational institutions, with primary focus to revolutionise k-12 education. Furthermore, NEWTON virtual labs are also designed with disabled students and their specific requirements in mind, as this is another aspect that is lacking in most existing virtual labs. NEWTON pilot schools include special secondary schools with students with hearing impairments.

While inquiry-based learning is quite different to the traditional method of passive, time-constricted and protocol-driven traditional lab, it also develops students' skills in a more comprehensive way. The way we teach in labs, and what students can expect from them, should change to make full use of the potential of virtual labs. Changing educators' and learners' opinions on how practical skills are taught will provide its own challenges. Students must learn time management, collaborative and peer-assisted learning, share ideas in online discussion forums, to make decisions and design experiments based on information obtained to fully participate in active, enquiry-based learning [6].

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 688503.

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