3DVL@ES:

A 3D Web-Based Virtual Laboratory for Collaborative Learning in Experimental Science Practical Work

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ABSTRACT

This paper introduces a virtual laboratory that aims to support the quick development and easy assimilation of practical works by learners and exchange documents between them via a shared virtual space. The proposed laboratory, named 3DVL@ES (web-based 3D virtual laboratory in experimental science), defines an agile design process to automatically generate 3D pedagogical web applications and provide very appreciable interactivity, flexibility, and collaboration for practical works development. Also, 3DVL@ES includes the specification of learners' interactions and collaborations on a unified application model to assist and automate the creation of new 3D interfaces related to practical work in experimental sciences. 3DVL@ES has been applied in a real case study of Daniel's Battery. The obtained results have been compared with other virtual laboratories to show the usefulness of 3DVL@ES. Experimental results show that 3DVL@ES laboratory easily achieves complex practical works with the integration of cooperation and collaboration aspects.

KEYWORDS

3D Interface, 3DVL@ES, Collaboration, Cooperation, Interaction, Practical Work, Virtual Laboratory

INTRODUCTION

With the rapid and continuous spread of the COVID-19 pandemic, distance learning has become the only way in the world to ensure learning at all levels. Distant learning offers online theoretical courses on education institutes during COVID-19 but also introduces considerable learning challenges when it comes to engineering and experimental science practice works, not only in providing online

courses and tutorials such as Moodle (Rice 2015) but also to ensure effective collaboration for online learning during COVID-19. When learners carry out practical experiments, they will understand the theoretical concept in more depth. Therefore, virtual laboratories are needed in the COVID-19 pandemic to meet the growing demand for distant practical works. Therefore, it is a question of how to design and develop 3D web applications to meet the collaborative requirements of learners and provide them the opportunity to practice what they learn in the theoretical courses in a similar way to traditional laboratories.

Several research works that focus on the development of Virtual Laboratories (VLs) are available online and freely integrated into universities (Rice 2015; Abramov et al. 2017; Mostefaoui et al. 2017; Broisin et al. 2017; Astutik et al.2018; El Kharki et al.2018; Wästberg et al. 2019; Carlos et al. 2019; Salame et al. 2019; Wahyono et al.2020; Kolil et al. 2020; El Kharki et al. 2020), but the use of these virtual laboratories is still limited compared to traditional laboratories. Currently, researches focus on the design and development of advanced VLs (Carlos et al. 2019; El Kharki et al. 2020; Wahyono et al. 2020). However, the majority of learners are facing difficulties in finding suitable VLs that ensure typical learner interactions and remote collaborations during COVID-19 (Mechta et al. 2012; Wästberg et al. 2019) in the field of experimental sciences. Thus, a remote collaboration between learners is essential to successful practical work. This kind of learning offers significant benefits such as reduced effort and increased efficiency for learners who specify and realize their practical works and interpret related test results. In addition, it would also allow for better learner engagement. Thus, remote collaborative and cooperative interaction must be considered to improve the quality of learning when designing and implementing VLs.

Few solutions take advantage of collaboration between learners within virtual environments. In this context, some VLs (Astutik et al. 2018; Radhamani et al. 2021) use only individual learning or data collected by the teacher. Therefore, the best way to fully reach the objective of VLs in a COVID-19 is not only to individual work but also to keep in mind that a VL is suitable for many learners and workgroups which have to cooperate together towards realizing the same unique global aim, good practical work with reduced efforts and time.

In this paper, we design and develop a web-based 3D virtual laboratory for collaborative leaning of practical works named 3DVL@ES in the field of experimental sciences such as physics, chemistry, biology...etc. This laboratory aims to assist learners to understand easily course concepts through visual practical work and to collaborate and share knowledge within a common virtual space. The novelty of the proposed virtual laboratory compared to existing virtual laboratories by designing a generic 3D application web-based model for experimental sciences. Besides it implements distributed learning tasks with multiple interactions mechanism that will give the practical work flexibility and reusability needed to carry out large-scale practical works and help learners to assimilate new practices through collaborative and cooperative learning strategies. The proposed laboratory defines an agile design process to automatically generate 3D pedagogical web applications and provide very appreciable interactivity, flexibility, and collaboration for practical works development. It explores the effectiveness of using virtual collaborative experiments on student's level of enhancement of learning outcomes and cognitive skills. Also, LV3D@SE includes the specification of learners' interactions and collaborations on a unified application model to assist and automate the creation of new 3D interfaces related to practical work in experimental sciences. Our virtual laboratory development is motivated by keeping the benefit of collaboration and cooperative interactions to achieve practical work effectiveness.

The main contributions of this paper are summarized as follows:

- The proposed virtual laboratory applied an optimized pipeline for virtual construction of practical works that allows designers to specify and automatically test generated 3D pedagogical web applications for collaborative hands-on learning.

- The proposed virtual laboratory combined visual interaction techniques to select 3D objects based on the learning pedagogical domain. These techniques are used to specify simple and complex 3D interactions on these objects within a 3D interface to ensure collaboration and cooperation during the realization of practical works.
- Finally, we have conducted an experimental evaluation of the proposed virtual laboratory on a real-life case study of Daniell Cell. A comparison between the proposed laboratory and two other virtual laboratories: Praxilabs (3D Praxilabs Simulations, 2021) and PhET lab (Salame et al., 2021) using a learner questionnaire has also been achieved.

The rest of the paper is organized as follows. Section 2 presents some limitations of existing virtual laboratories. In section 3, the design process and the application description are detailed. In section 4, the development process of the proposed virtual laboratory has been presented. In section 5, the experimental evaluation and comparison have been performed. Finally, section 6 concludes the research paper.

MOTIVATING CASE STUDY: DANIELL CELL

To understand the concepts used in this paper and to illustrate the purpose of this work, it is necessary to provide some useful definitions through a motivating case study in several experimental sciences.

Definition 1 (Virtual 3D Object). A virtual 3D object is the representation of real equipment in 3D. The equipment can be manipulated by learners in the field of experimental sciences. Each object is defined by an identifier and unique name. We distinguish three types of objects according to the field of experimental sciences: material, liquid, and solid products science. Each object has a specific role in one or more experiments performed within a 3D web application.

Definition 2 (Simple and Complex Learning Task). The learning task can be either a simple learning task or a complex learning task. A complex learning task is cooperation and collaboration of multiple interaction tasks. A simple learning task is defined by a set of interactions on 3D objects: moving, rotating, scaling, and selecting. For example, in the experiment of Daniell cell who has not-so-good diet situation that can be modeled as a complex learning task, which consists of a pouring task. The pouring task with a set of successive interactions: select object ® moves up ® rotated it, is considered as a simple interaction task.

Definition 3 (Cooperative Pedagogical Interaction Task). A cooperative pedagogical interaction task is a set of independent interaction tasks in which the learner performs a task independently of the other learners in order to evaluate the individual efforts and assigned responsibilities of each learner. For example, in the experiment of Daniell cell, learner#2 selecting the test tube and learner#2 selecting the beaker.

Definition 4 (Collaborative Pedagogical Interaction Task). A collaborative pedagogical interaction is a set of dependent interaction tasks in which learners collectively work towards a common goal. A typical example in the experiment of Daniell cell is learner#1 constructs the first half- pile and learner#2 constructs the second half- pile.

Our case study involves assisting learners in the experiment of Daniell cell of chemistry domain. The experiment's purpose is to manage all learning tasks of the chemistry domain efficiently by enhancing the learning guide and reporting learning task problems. The experiment of Daniell cell balances charges between electrodes and an electrolyte as well as the ionic species in a solution. The experiment consists of a node (zinc plate immersed in a zinc sulfate solution) and a cathode (copper plate immersed in a copper sulfate solution). When connecting these solutions using a salt bridge, electricity is generated. The objective of this case study is to develop a virtual experiment for collaborative learning on how to design the Daniell cell to generate and balance electricity. Figure 1 shows the operating principle of the Daniell cell.

Figure 1. Operating principle of Daniell cell (Saslow 1999)
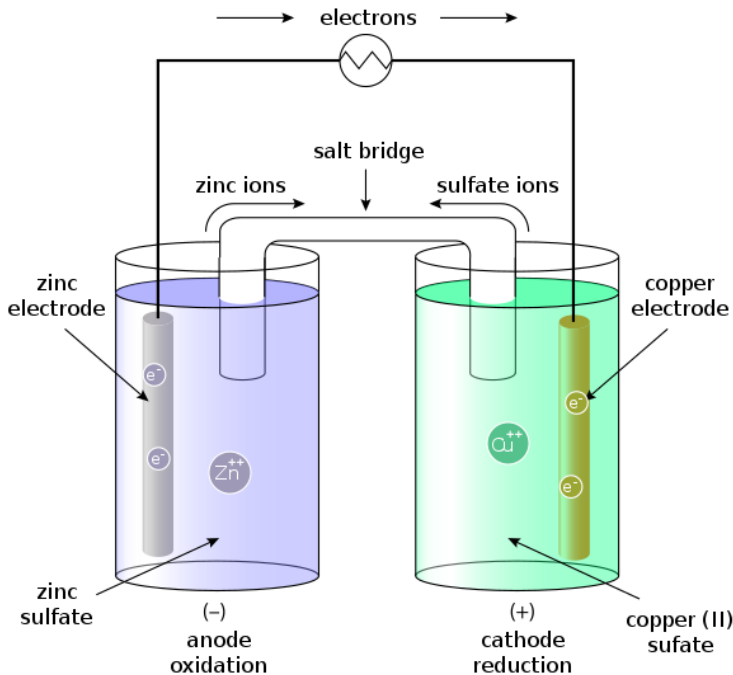
The design of the virtual experiment is based on knowledge of equipments in the chemical domain, and reaction equations and it combines different types of chemical symbols and learning skills. When it comes to students working cooperatively and collaboratively does not necessarily come easy and may require a formal change of practical work methodology for everyone involved.

Let us suggest this scenario: we are interested in the Daniell cell collaboratively realized by two learners (learner#1 and learner#2) using different interactive devices (smartphone and laptop) in virtual workspaces. Various 3D objects represent experimental equipment. Table 1 details a list of available objects and equipment in the workspace room.

In our case study, the system finds learning tasks from the worksheet and sets them to both learners on their interactive devices. The learner' agenda can be used to identify various learning tasks from the beginning until achieving the practical work. The learning tasks can be performed in a cooperative and/or collaborative manner. Below, we give a short detail about the tasks. Cooperatively, learner#1 constructs the first part of the Daniell cell, and learner#2 constructs the second part of the Daniell cell. Learner#1 pours 20 ml of zinc sulfate solution into the test tube and then he places the zinc blade in the beaker. Learner#2 pours 250 ml of copper sulfate solution into the test tube and then he places the copper blade in this beaker. When it is time for learners to work collaboratively, both learners connect the two beakers with a salt bridge and connect the voltmeter to the pile terminals. Table 3 details a list of learning goals for each learning task and its reaction equations, type of tasks, and learners' interactions.

The scenario described above can raise the problem of the time delay and accurate results of different learners' competencies skills (*e.g., a scenario when leraner#1 performs from his laptop the first part of Daniell cell, and the learner#2 performs the second part of Daniell cell from his smartphone*). The system must ensure effective cooperation and collaboration between learners towards common goals but poses certain challenges due to different learners' skills and different characteristic of mobile devices in obtaining high precision scientific results. To this end, we propose a new virtual

Table 1. Different equipments in the virtual workspace room

Solid equipment	Liquid equipment
A copper blade (orange). A zinc blade (white). Two beakers. A salt bridge. A voltmeter. Electrical wires. Bottle of zinc sulfate. Bottle of copper sulfate.	Copper sulfate solution Zinc sulfate solution

laboratory that efficiently manage complex learning tasks with appropriate interactions (*e.g., How do we guide it? and How do assist learners' during and after experiments?*). The proposed virtual laboratory needs to provide:

1. A generic unified practical work model and incremental guidelines for experimental sciences to facilitate the modeling and generation of 3D web applications,
2. Managing simple and complex tasks in an efficient way and optimizing the user's experiences (*i.e., parallel processing of incoming tasks simultaneously by different learners and managing effectively complex tasks in virtual cooperative and collaborative pedagogical interactions*).

LITERATURE SURVEY

Our work deals with a 3D virtual laboratory that generates web applications for collaborative learning based on a unified design model and systematic guidelines. Many virtual and remote laboratories have been developed in the past decades (El Kharki et al. 2016; August et al. 2016; Abramov et al. 2017; Niandou et al. 2017; Mostefaoui et al. 2017; Broisin et al. 2017; Astutik et al. 2018; El Kharki et al. 2018; Gardner et al. 2018; Stauffer et al. 2018; Carlos et al. 2019; Gardner et al. 2019; Wästberg et al. 2019; Wahyono et al. 2020; Bogusevschi et al. 2019; Correia et al. 2020; Kolil et al. 2020; Salame et al. 2021; El Kharki et al. 2021). They have been used for a specific educational field and has not been applied to a wider class of disciplines. We distinguish two main laboratories: physical laboratory and virtual laboratory. We will focus only on virtual laboratories as detailed in the next section. We have reviewed recent virtual laboratories related to the COVID-19 pandemic.

Recently, Labster Company has developed advanced interactive laboratory simulations for different learning domains, including chemistry, physics, medicine, biology, etc. They aim to provide teachers with various laboratory simulations that can be used to teach learners in experimental sciences. They cover various specialties. (Gardner et al. 2018) developed four simulations in the field of biochemistry. (Stauffer et al. 2018) proposed five simulations in the field of medicine, specifically the basic concepts of genetics. In the field of biology, authors developed five simulations (Stauffer et al. 2019).

(Gardner et al. 2019) developed four further simulations for learning human genetic diseases. These environments incorporate games, multiple-choice questions, and text to enable learners to fully understand basic concepts. The level of engagement and immersion of learners shows that the Labster is integrated with several learning management systems (Blackboard, Canvas, Moodle, Sakai, etc...).

(El Kharki et al. 2021) designed and developed a web-based virtual laboratory for physics teaching in Moroccan universities. This virtual laboratory consists of 12 virtual assignments of the physics curriculum modules, deployed in 12 sciences faculties in Morocco. The laboratory is a computer simulation implemented in JavaScript and integrated into an interactive learning environment based on Moodle platform.

A free virtual laboratory provided as an open-source environment is the Physics Education Technology Project (PhET). PhET was founded in 2002 by Nobel Laureate Carl Wiman at the University of Colorado at Borun (Salame et al. 2021). The PhET aimed to teach physics, mathematics, chemistry, biology, and earth sciences worldwide using free interactive simulations translated into 65 languages. Several virtual laboratories in universities have integrated PhET such as the chemistry laboratory at the University of Colorado (Correia et al. 2019). All PhET simulations are written in Java, Flash, and HTML 5, and can be run online or downloaded to a computer.

All these virtual laboratories perform practical work learning on the web using mobile devices with sometimes-great difficulties in carrying out large-scale practical works in experimental sciences. This leads to performing better and in real-time. Another major drawback is the systematic guiding process and fuzzy evaluation of the quality of practical work learning in colleges and universities. It requires programming skills to create interactive web 3D learning applications and sciences domain skills to produce a smooth acquisition of experimental concepts. The quality of learning is closely linked with the quality of the final 3D practical work and its precise results.

The company Praxilabs has developed other virtual laboratories for scientific experiments. These laboratories are web-based 3D interactive simulators in several fields:

1. **Chemistry:** a set of simulations of chemistry experiments are offered to learners in general, analytical, and organic chemistry,
2. **Physics:** the Praxilabs experiments available in the field of physics cover several specialties: nuclear physics, thermodynamics, electricity, etc.
3. **Biology:** to enrich the Praxilabs 3D environment several simulations have been added recently in the field of biology ranging from using microscopes to understand biology to DNA extraction and genetic cloning with immersive experiments.

Praxilabs simulations are available in two languages: Arabic and English and can be integrated into the current LMS. Access to Praxilabs is now via a free user account but there is partial access to six simulations. After using some simulations in biology and physics it was found that they used Unity 3D for developing these simulations. The user interface is user-friendly for performing the experiments. Nevertheless, there is no guarantee that the results of practical work are of high quality before the teachers generate the 3D web application. Moreover, an effective strategy is needed in practical work to meet precision requirements and provide quality practical work.

We have identified the common limitations of the studied laboratories, particularly for integrating remote collaboration between learners during practical work (see table 2). The integration of these VLs in LMSs enables learners to communicate with each other. For this purpose, we aim to create a virtual laboratory that meets the criteria of remote collaboration and cooperative interactions (a new concept called virtual pedagogical interaction). The novelty of our approach is to provide: (1) 3D pipeline designing and generating 3D web application process; (2) task-interactions based process representing cooperative and collaborative activities regarding practical work. These contributions improve the performance of the learning process of learners while identifying complex tasks. In case of complex tasks are identified, the system calls the practical work generator, which is responsible for generating a list of cooperative and collaborative pedagogical interactions.

3DVL@ES: A WEB-BASED 3D VIRTUAL LABORATORY FOR EXPERIMENTAL SCIENCES

The 3DVL@ES virtual laboratory aims at assisting learners to accelerate the realization of practical work in the field of experimental science as well as ensure cooperative and collaborative interactions and support the creation and exchange of practical work documents. The 3DVL@ES laboratory provides

automated generation of 3D web-based applications for collaborative learning of practical works. This section sheds light on the design and specification model of 3DVL@ES, the conceptual design of the 3D-web learning applications, and the practical learning concept related to virtual collaborative learning.

General Architecture

Figure 2 shows a general overview of 3DVL@ES. The architecture consists in two main modules:

- The Collaborative Interaction System represents the functional part of 3DVL@ES that includes the learner's interactions/interfaces and communication tools.
- The Graphical 3D Interface Manager represents the structural part of 3DVL@ES, which manages learner tasks and 3D objects.

3D Graphical Interfaces of 3DVL@ES

The 3D interface is a three-dimensional workspace that contains all handled tools, products, and equipment during the experiments that are represented by virtual 3D objects, specified and placed. This workspace is made up of several spaces such as the practical room, the furniture, the used material, users (learners /teachers), and a toolbar of 3D objects, etc. Some 3D objects used in a 3D interface of the Daniell cell can be shown in figure 3.

Collaborative Interaction System of 3DVL@ES

The key idea behind 3DVL@ES laboratory is to facilitate collaborative and cooperative interactions among learners when performing their practical works. Figure 4 presents the interaction mechanism in a virtual laboratory based on a common virtual space. The diagram presents two scenarios:

Table 2. Comparison of related works

Related Work	Access Type	Cross-Platforms	Genericity	Workspace	Cooperative Interactions	Collaborative Interactions	Practical Assessment
Abramov *et al.* 2017	Paid	✓	✓	3D	✓	✗	✗
Niandou *et al.* 2017	Paid	✗	✓	3D	✓	✗	✗
Mostefaoui *et al.* 2017	Paid	✓	✓	3D	✓	✓	✗
Astutik *et al.* 2018	Free	✗	✓	2D/3D	✓	✓	✗
El-Kharki *et al.* 2018	Paid	✗	✗	2D	✓	✗	✓
Stauffer *et al.* 2018	Paid	✗	✓	3D	✓	✗	✓
Bogusevschi *et al.* 2019	Paid	✗	✓	3D	✓	✗	✗
Salame *et al.* 2019	Free	✗	✓	2D/3D	✓	✗	✗
Correia *et al.* 2019	Free	✗	✓	2D/3D	✓	✗	✗
Wästberg *et al.* 2019	Paid	✗	✗	3D	✓	✗	✗
Gardner *et al.* 2019a	Paid	✗	✓	3D	✓	✗	✓
Gardner *et al.* 2019b	Paid	✓	✓	2D/3D	✓	✗	✓
Kolil *et al.* 2020	Paid	✗	✗	3D	✓	✗	✗
El Kharki *et al.* 2021	Paid	✗	✗	2D	✓	✗	✓
Carlos *et al.* 2021	Paid	✗	✗	3D	✓	✗	✓
Salame *et al.* 2021	Free	✗	✓	2D/3D	✓	✗	✗
Praxilabs 2021	Paid	✓	✓	3D	✓	✗	✓

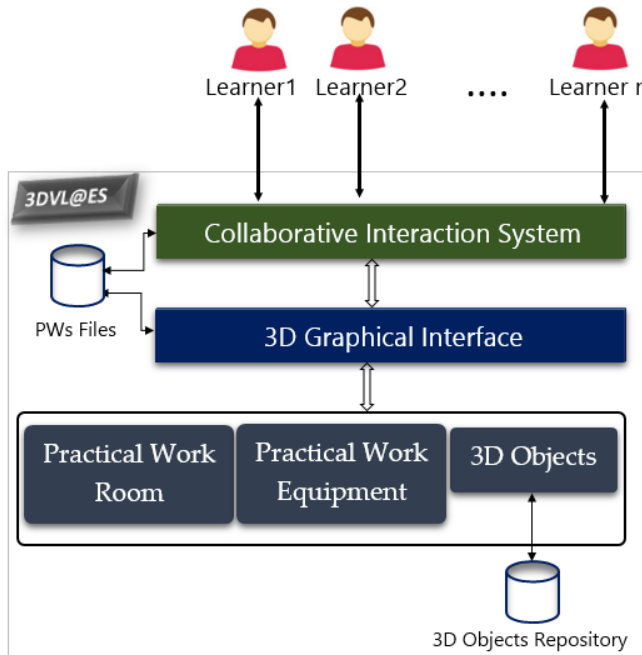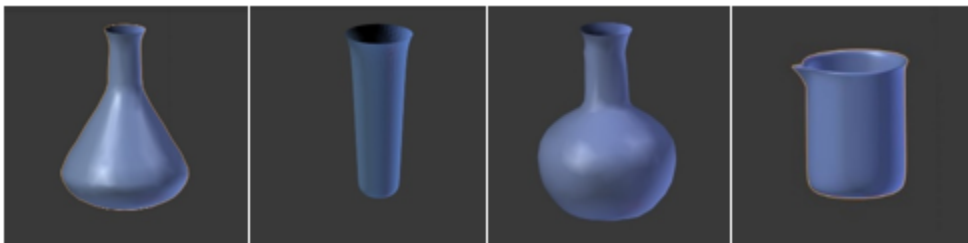**Figure 2. Collaborative learning architecture**

Figure 3. Example of 3D objects used in 3D interface

- If only one learner performed the practical work, he enters their identifiers through a web browser to the VL①. Since the VL receives the identifiers, it checks the authentication of the learner. If the learner's credentials are correct, the learner selects practical work. Otherwise, access is denied. Then, he selects 3D virtual objects , needed for practical work through a 3D interface f. After that, he prepares his tools using 3D workspace and performs a set of pedagogical interaction tasks on 3D objects using 3D interface. Once all tasks have been executed, the pedagogical resources are updated and saved ‡.
- If more than one learner performed the practical work…, each learner enters their identifiers through a web browser to the VL① in order to check the authentication of each learner. Each learner is associated with a 3D interface, which allows for performing tasks. Tasks can be simple or complex. If it is a simple task, the virtual pedagogical interaction system keeps the learner inside a 3D workspace to perform their simple pedagogical interaction tasks f on 3D objects†. If collaborate, the shared interaction system ensures coordination and control of simultaneous

Figure 4. Collaborative interaction system within 3DVL@ES
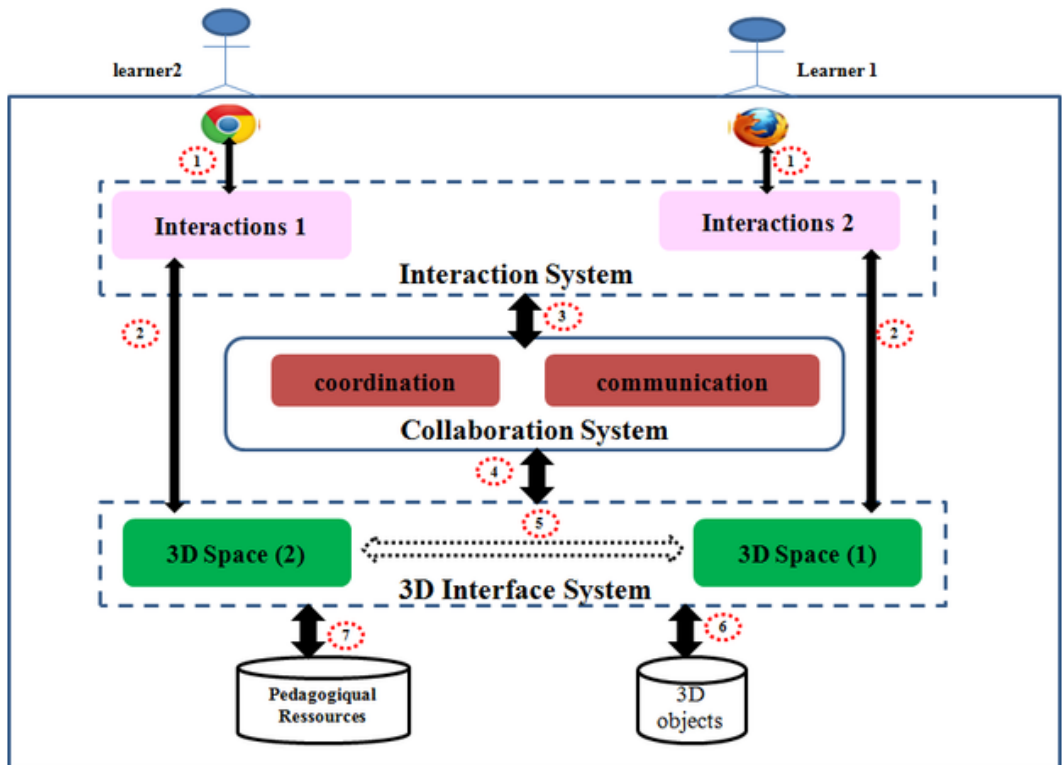
access and the sharing of updates between the two learners' spaces…. Once the whole task has been executed, the complete practical work is saved‡.

A great benefit of interactions in the 3DVL@ES virtual lab depends on two main communication mechanisms for document exchanges and collaborative interaction tasks: (1) - an Internet-based approach and (2) - a P2P approach. The first approach provides the sharing of documents between different remote learners. The second approach can be used when a connection is not available. The learners use a shared 3D interface between different 3D spaces to create virtual and remote collaborative interactions. 3DVL@ES provides a visual medium for cooperative and collaborative interactions. Many different complex interactions are available for learners to access the shared virtual space.

Use Case Diagram of 3DVL@ES

In our system, we can identify two main actors as shown in figure 5:

- **Visitor.** A visitor can visit 3DVL@ES and register to access the main functionalities of 3DVL@ ES He can later become a member.
- **Learner.** A learner can connect to 3DVL@ES using his identifier and his password and profits from the following services: (1) access to a 3D workspace, (2) add and delete a 3D object from the 3D interface, and (3) apply virtual interactions on the selected objects such as navigation, selection, manipulation, and application control.

Figure 5. Use case diagram of 3DVL@ES
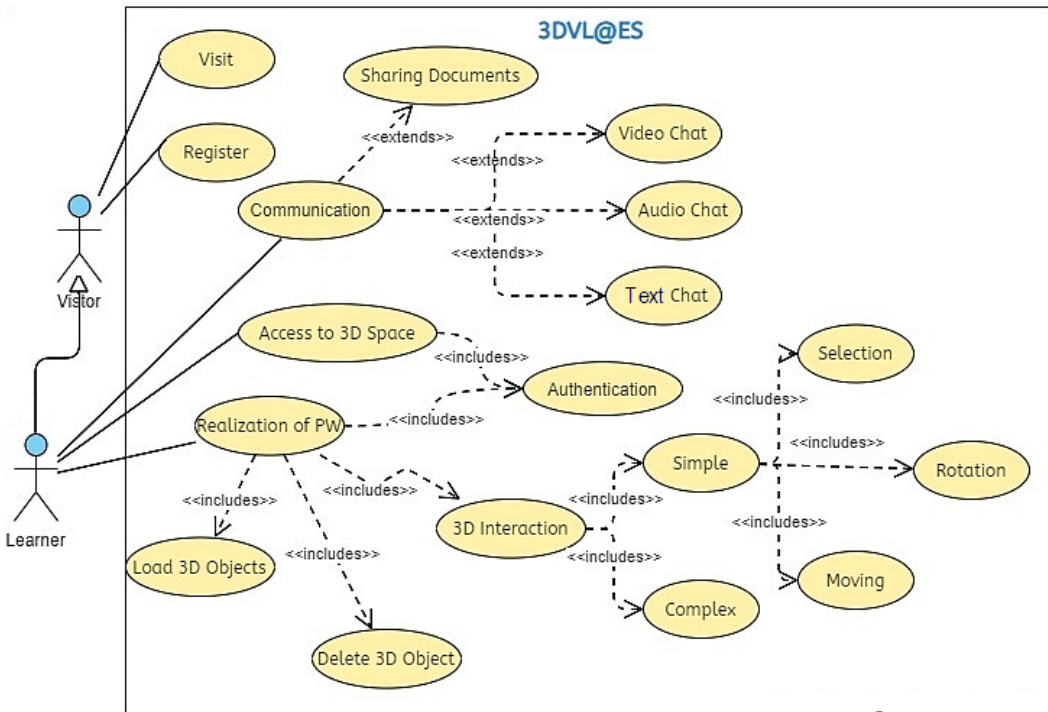
Unified Description Model of 3DVL@ES

All practical works require rigorous specification and graphical modeling phases. A generic unified description model is a visual representation of all kinds of practical work for experimental sciences. It allows us to add a 3D HMI layer and an interaction layer to the 3D Web-based applications. We focus on a unified model for the description of practical 3D Web-based applications that groups three sub-models and their relationships with the task, interface, and interaction phases. Figure 6 shows an overview of the proposed multi-faceted unified model for the design of web-based 3D applications. In such a model, we identify concepts from three phases of the design process and define the 3D web-based learning applications and their practical work concepts as four facets as follows:

- **The 3D Object Facet:** The unified description model is based on 3D applications of experimental sciences that are constituted of 3D objects. Each object is defined by an identifier and unique name. It instantiates several objects according to their types and roles. We distinguish three types of objects according to the field of experimental sciences: *material*, *liquid,* and *solid products*. These virtual objects are used to represent real objects that will be manipulated by learners in the field of experimental sciences. For example, *beaker, Florence, and test tubes* are materials that can be used for many practical tasks and are available in all experimental science laboratories. However, *desalted water, copper sulfate solution,* and *zinc sulfate solution* are examples of liquid products. We have also a *zinc blade*, and *Copper blade* are examples of steel products. The learner pours *20 ml* of *zinc sulfate* solution into the *test tube*. This example illustrates two used objects: *zinc sulfate* solution as a liquid product and *test tube* as material to perform the pouring task.
- **The 3D Graphical Interface Facet**: A 3D interface is a key concept that defines the layout of objects dedicated to displaying and performing various experiments on different domains of physical, chemistry, etc. A 3D interface can contain one or more 3D objects. Each object has a

Figure 6. Unified description model of 3D Web-based applications for PWs
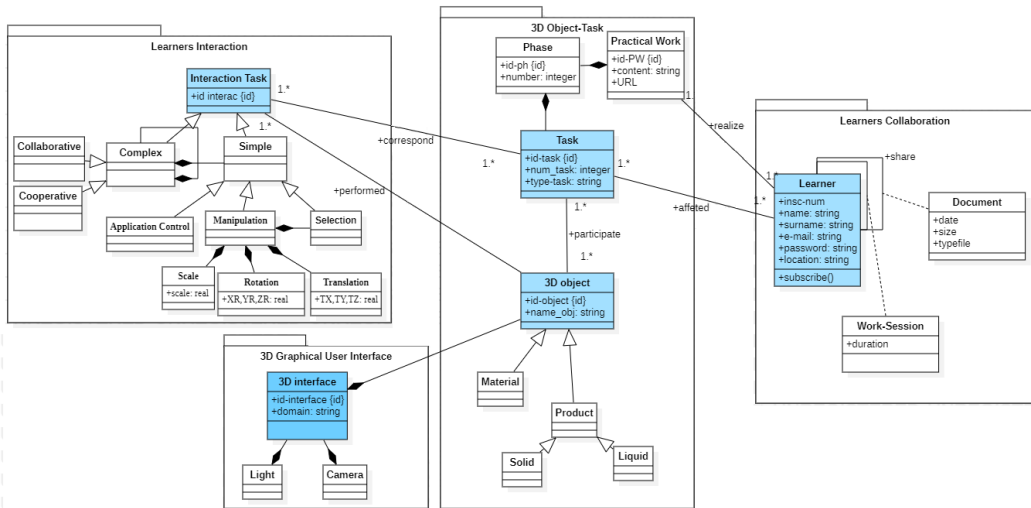
specific role in one or more experiments performed within a 3D web application. For instance, a 3D interface is a specific room for each laboratory equipped with desks, chairs, cabinets, and workspace. The learner selects the required laboratory objects to display them on the 3D interface (*workspace*).

- **The Learner Interaction Facet**: describes the HMI related to object manipulation interactions: moving, rotating, scaling, and selecting. For instance, as already mentioned in the example of the object-spot model, the *pouring* task is performed by the following set of successive interactions: select object ® moves up ® rotated it.

- **The Learner Facet**: describes the learner profile and its different information (*name and surname of the learner, email, password, location, etc.*) as well as collaborations between the different learners. The collaboration favors the sharing and exchange of experiences and documents related to the practical work of a specific field. However, in the case of distributed groups of learners, the sharing of document information in heterogeneous platforms is difficult. Therefore, ephemeral or temporary communities can be used whose interest to participate to perform the practical work.

Control of Practical Works on 3DVL@ES

1. A learner will log in first with his identifier and his password to enter into the.
2. A learner can create a new workspace of the practical work currently done by clicking the 3D space button.
3. After selecting a domain, he/she will see the list of available 3D objects and can select one from them to perform simple or complex interactions (actions).
4. Further, a learner can perform simple interactions on 3D objects that consist of selecting and moving an object individually.
5. Learners can also collaborate on the same workspace, which requires control, coordination, and sharing of such workspace.

PIPELINE PROCESS OF 3DVL@ES

This section presents a pipeline design process for generating 3D Web-based applications. It enables the visualization of 3D objects and concepts that best fit the experience's domain and the intellectual level of the learners. The 3DVL@ES takes as inputs the pedagogical requirements and tasks as a text file in order to generate the pedagogical 3D web application. This kind of approach is called the incremental learning process where the simple interactions pedagogical tasks are first generated and then incrementally refined to produce cooperative and collaborative pedagogical interactions. Figure 7 shows an overview of the proposed approach that consists of four successive stages described below:

Stage 1: Application Data

The application data stage allows identifying performed tasks by the learner via a 3D web application based on the learning needs and specification of the worksheet. Two types of tasks: cooperative (e.g. tasks that are performed individually) and collaborative (e.g. tasks that are performed by two or more learners). Figure 8 presents the structure and summary of the txt worksheet file.

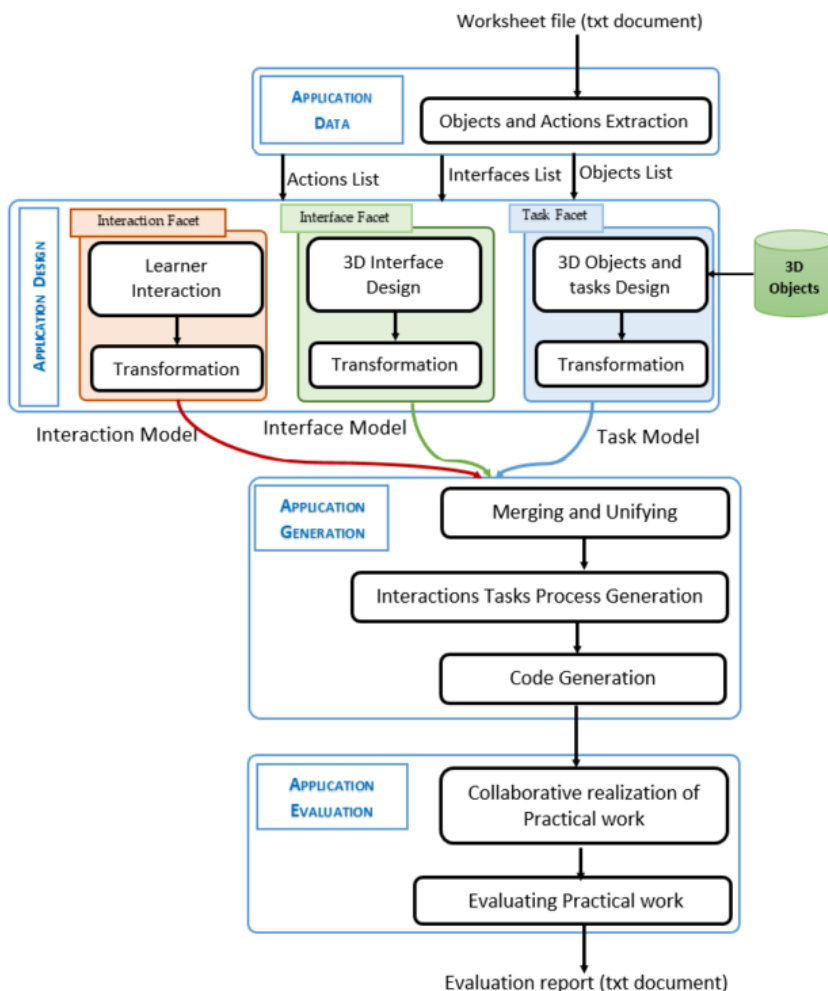Figure 7. 3D pipeline designing and generating 3D web application process

Figure 8. Example of worksheet summary

```
Test tube
Pours :  20 ml : Sulphate of zinc solution
Pours : 250 ml : Sulphate of copper
solution
Beaker
Places : zinc blade
Places : copper blade
…..
```

Stage 2: Application Design

Step 2.1:   **Construction of Task Learning Model.** We now have a list of actions without dependencies and a list of 3D objects. The objective of this step is therefore to identify the independent and dependent tasks. The system transforms the relevant tasks list into a hierarchical process. The hierarchical process consists of three levels: complex tasks layer, simple tasks layer, and common 3D objects layer for all tasks. Figure 9 presents an illustration of complex tasks, three simple tasks, and three 3D objects of the Daniell cell. The hierarchical learning process promotes systematic guidelines and the effectiveness of the learning of practical works. The system checks if the new task is yet to exist and creates a new root branch for it. Alternatively, in the case of complex tasks that have subtasks, if a sub-task already exists in a hierarchical process, the system will assign it to its parent complex task. When the system finishes, it produces the hierarchical process as shown in Figure 9 of cooperative tasks (e.g., tasks that are performed individually) and collaborative (e.g., tasks that are performed by two or more learners).

Figure 9. Building a hierarchical learning process from the actions list
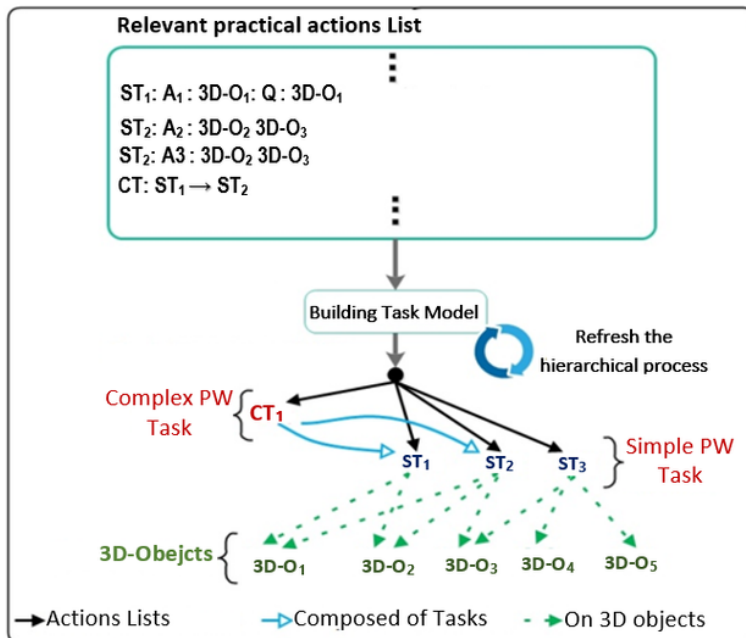
Step 2.2:   **Mapping Learning Tasks to Learning Interactions.** In this step, the VL maps each task to a set of learning interactions. Two types of interactions are used: cooperative and collaborative. The system explores the learning process to convert learning tasks into learning interactions taking into account all the dependencies between the complex tasks and their simple tasks. Then we iterate all common 3D objects of the process to assign them to each interaction.

Step 2.3:   **3D Interface Design Model.** We have a 3D-Table Interface Model. The model can contain all handled tools, products, and equipment during the experiments that are represented by virtual 3D objects, specified, and placed in a three-dimensional workspace (3D interface).

Stage 3: Application Generation

Step 3.1:   **Merging Task – Interface – Interaction Model.** We have merged all models to an instance of our unified description model, which is used to generate 3D-web-based practical work applications.

Step 3.2:   **Code Generation.** The teacher can automatically generate source code for 3D web-based applications and quickly evaluate the application. The code generation is based on a code generator template. If the teacher (e.g., designer) feels that the generated 3D web-based application does not match the learner's needs and required tasks, he/she can go back to a previous phase and redesign it. The designer can add, modify and/or delete particular 3D objects, or particular interactions. Moreover, it is no longer possible to design a 3D web application for practical work without interactions. The learners will test the generated application during collaborative sessions.

Stage 4: Application Evaluation

The teacher evaluates the learner's ability to realize the practical work individually and collaboratively. Thus, he provides the VL with the final evaluation scores for learners. The proposed approach evaluates the practical work in an autonomous and collaborative manner and computes the final score of the learner.

IMPLEMENTATION AND VALIDATION OF 3DVL@ES

Our prototype is implemented in JavaScript and Blender 3D. The prototype can help learners experiment with practical work using a suitable room according to its discipline. It also provides learners with multimedia communication facilities and even Peer-To-Peer (P2P) sharing of documents. It enables a learner conducting a scientific experiment to collaborate with other learners, which enhances the learners' experiences and reduces the time of carrying out the practical work. In addition, the prototype is highly flexible for the specification and design process of 3D web applications. It offers easy virtual access and allows collective practical work and knowledge sharing. Several development tools and script languages have been used in developing the 3DVL@ES laboratory.

Possible pedagogical virtual interactions

The possible case studies are varied and vast. For example, we have used our framework to guide experiments in the Daniell cell. When a learner connects to the 3DVL@ES lab and selects his/her discipline and the virtual laboratory, he/she displays and discovers the appropriate discipline lab room including the workspace to carry out experiments. For the Daniell cell case study, Table 3 depicts the different tasks to be performed in the Daniell cell by the learner. Daniell's cell experiment consists of two main complex tasks (*construction of first half-pile and construction of second half-pile task*) related to specific learning goals. Our VL maps these tasks to sub-tasks or actions (*e.g., the first half-pile consists of tasks: the learner pours 20 ml of Zinc Sulfate solution into the test tube and then places the Zinc metal in the beaker. motion detection using motion service*). Each action is transformed into a set of interactions (*e.g., the first action mapped to a set of interactions: select Zinc Sulfate, move the tube towards the beaker, and rotate the beaker to pour 20 ml of Zinc Sulfate solution*).

Table 3. Decomposing learning tasks and interaction of Daniell cell on a group of learners

	Learning Goals	Learning Task	Type of Task	Learning Actions	Learning Interactions
Learner#1	An oxidation half-reaction $Zn= Zn^{2+} + 2e^+$ **Goals** - Learner's ability to use tools. - master tasks and learning actions relate to an oxidation - Learner's ability to construct the half-pile from half-reaction equations.	Construction of the first half-pile	Cooperative	The learner pours 20 ml of Zinc Sulfate solution into the test tube.	Select Zinc Sulfate
					Move the tube towards the beaker
					Rotate the beaker to pour 20 ml of Zinc Sulfate solution
				The learner places the Zinc metal in the beaker.	Select the Zinc metal object
					Move the Zinc metal towards the beaker
					Move again the Zinc metal towards the beaker
Learner#2	A reduction half-reaction $Cu^{2+} + 2e^- = Cu$ **Goals** - Learner's ability to use tools. - master the actions. - Learner's ability to construct the half-pile from the second half-reaction equations.	Construction of the second half-pile	Cooperative	The learner pours 250 ml of Copper Sulfate solution into the test tube.	Select Zinc Sulfate
					Move the tube towards the beaker
					Rotate the beaker to pour 250 ml of Copper Sulfate solution
				The learner places the copper metal in the beaker.	Select the Copper metal object
					Move the Copper metal towards the beaker
					Move again the Copper metal towards the beaker
Both Learners: Learner#1 and Learner#2	Reduction $Zn + Cu^{2+} = Zn^{2+} + Cu$ Oxidation **Goals**	construction of Daniell cell	Collaborative	Learners place two beakers side by side.	Select the first beaker
					Move the first beaker to the second beaker
					Deselect the beaker
				Learners connect two beakers by a salt bridge	Select a salt bridge
					Move a salt bridge to two beakers
					Make a salt bridge on two beakers
					Deselect a salt bridge
				Learners connect electrodes to a voltmeter.	Select a voltmeter
					Select the first electrode
					Move it to a voltmeter
					Display voltmeter results
	Goals - Learner's ability to understand the theoretical concepts. - Learner's ability to display and plot the results - Learner's ability to repeat the experiment with another dosage to have new results	Voltage Measurement and establishing the report	Collaborative	The learner record voltage measurement on a voltmeter	Record the voltage value
					Plot the reaction equation
				Use the data and results to establish the report	The learner opens the editor to write the report,
					Share results and reports.
					video, audio, and text chat

Extracting Actions List from Worksheet. The first step consists of scanning the worksheet file. The system filters relevant 3D- object and actions lists. Table 3 shows a list of relevant actions of Daniell cell.

Mapping actions list to PW learning process. After the actions list extraction process, the system builds a practical work learning process and creates dependency links between the learning tasks and their 3D objects or with other learning tasks. This transformation is useful for enhancing learners' experiences and optimizing the practical work learning process.

Mapping learning tasks to interactions. The practical work can be carried out in two ways: individual, which involves a single learner, and collaborative, which involves at least two learners. We

distinguish two types of interactions: simple interaction and complex interaction. We aim to realize Daniell cell PW in a virtual lab by performing simultaneously cooperative tasks in an individual way that requires simple and complex interactions. Simple interactions include the addition and the selection of objects both individually and in cooperative tasks, and geometric manipulations either by moving, rotating, or scaling 3D objects. We show these interactions via an example of cooperative selection of 3D objects and an example of moving a 3D object.

- **Cooperative selection of 3D objects.** The first task (*construction of the first half- pile)* and the second task (*construction of the second half- pile*) of Daniell cell PW are cooperative tasks. Each Learner performs a task independently of other learners. Figure 10.a shows an example of *learner1* selecting the test tube and *learner2* selecting the beaker, both objects in green color to highlight the selection.
    - Moving a 3D object is one of the simple interactions that allows changing the position of this object from one place to another on the workspace to perform a practical work action. Figure 10.b shows how to change the position of the object from the middle of the table to the left.
    - Complex interactions include the sharing of a document, collaborative selection of 3D objects and geometric manipulations such as moving, rotating, and scaling the 3D objects.
    - Learners can communicate with each other in the shared communication space using chat tools and even share data and documents.
- **Collaborative selection of 3D objects.** Remote virtual laboratories provide learners the opportunity to conduct remote real/virtual experiments at home or anywhere through real-time communication. Practical work is defined by the set of behavioral changes that objects undergo when the learners interact with the interface to perform their tasks. Each learner works with his/ her own object, i.e., two learners can perform their practical activities of the course individually. For instance, each learner selects a different object to perform his/her tasks (see Figure 11).
    - *Case of adding an object on 3D interface.* When learner1 adds an object to the scene and if there is another learner2 who shares the same workspace "case of collaboration", it is necessary that the object appears in the other scene at the same time and vice versa. If learner1 selects "Object1, earner2 wants to select the same object. Learner2 cannot perform this "selection" until learner1 releases "Object1" (see Figure 11.a)
    - *Case of moving 3D object.* After selection, Learner1 can move the object to any new coordinates in the 3D Interface. Figure 11.b shows a situation where Learner1 moves an object in the working space and the new coordinates are updated at the same time.
- *Case of cooperative selection individually.* After the selection, each learner can rotate and move the objects. Figure 11.c represents this use case.
- *Case of rotating and moving objects.* After the selection, each learner can rotate and move the objects. Figure 11.d represents this use case.

Figure 10. Simple interactions:a) - selection of an object, b) - moving an object c) - completion of cooperative tasks

Finally, the practical work is ready to be finalized using advanced interactions arising complexity of synchronized access to objects, since learners share the same workspace in real-time. The participants feel as if they are working in real space (*space sharing*). For accomplishing Daniell cell practical work, we need to build and assemble the results of learner#1 (half grid1) and the results of learner#2's work (second half grid). Both learners connect the two beakers with a salt bridge and connect the voltmeter to the pile terminals (see Figure 12).

The learner uses a common virtual space in LV3D@SE chat to communicate with one or more learners. He can share their documents, and exchange messages and multimedia videos as illustrated in Figure 13.

Figure 11. Examples of collaborative and cooperative interactions: a) - adding an object, b) - moving an object, c) - cooperative selection of two different objects, d) - rotation and movement of objects
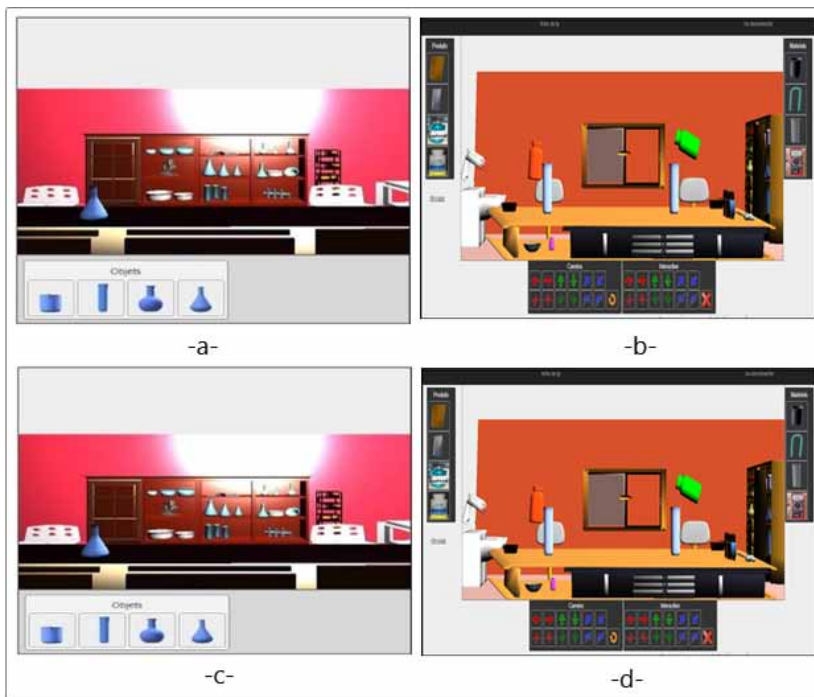

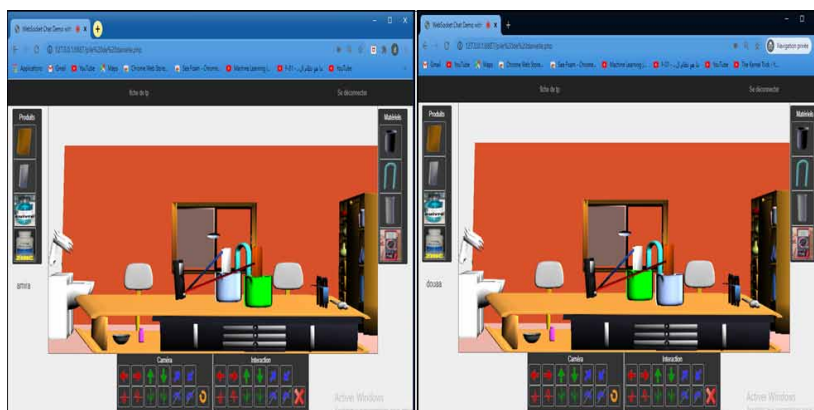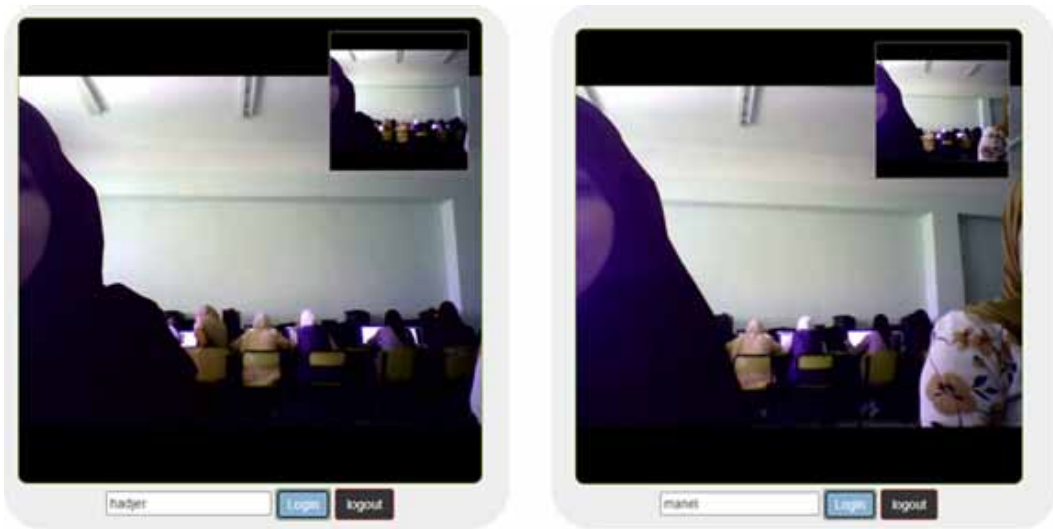Figure 12. Finalization of Daniell cell practical work

Figure 13. Example of video call

When the learner has finished his practical work, he must answer Multiple Choice Questions (MCQ) to properly assess his assimilation of new conceptual and chemical reactions of Daniell cell. He can also create a new session and display his evaluation results as shown in Figure 14.

EVALUATION OF VIRTUAL LABORATORY AND PARTICIPANTS

Evaluation criteria

To evaluate the proposed approach, a web-based 3D virtual laboratory for experimental sciences (3DVL@ES), we need to find a set of criteria that can meet learners' preferences and the experiment's context. For this purpose, we have chosen the genericity, interactivity as well as learning quality to evaluate the proposed virtual laboratory.

- **Genericity:** To evaluate the genericity of the proposed approach, we randomly do trials in the virtual environment. We will allow learners to perform freely and correctly the interactive behavior of their labs within a 3D online virtual laboratory.

Figure 14. Example of pedagogical MCQ
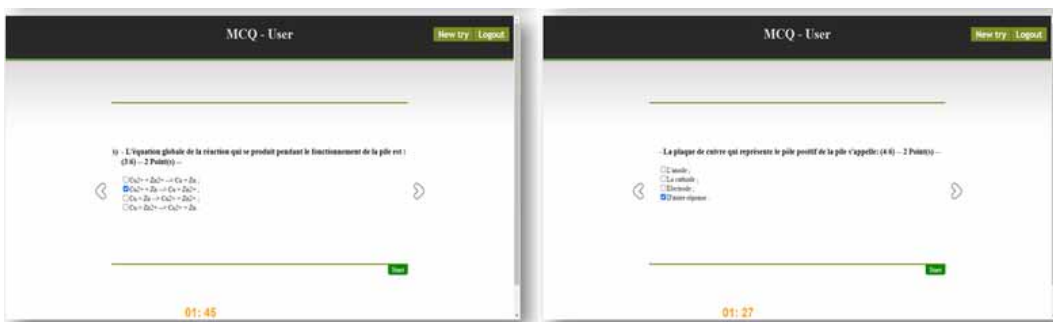
- **Interactivity:** In general, practical works require a high degree of interaction between the learner and the graphical interface (HMI), and among learners. This factor includes individual and collective participation in the learning of the course. This means that a learner actively participates during the task, communicates with other learners, and shares knowledge with them during the activity.
- **Ergonomics:** Designing 3D interfaces requires the representation of the lab in synthetic images to solicit the learner's sensory-motor competence in the field of virtual objects. In addition, the 3D interface shall accurately support the learner's requirements. Thus, we consider the ergonomic criteria (Bach et al. 2018) to facilitate the learning task and provide the learner with a flexible and useful interface.
- **Learning quality:** an important criterion for evaluating how to realize the practical using the virtual laboratory instead of a traditional laboratory.

Participants and Evaluation Strategy

The evaluation of the proposed approach was carried out over one month in two stages. Overall, the participants consisted of 30 learners from the Faculty Sciences at Ferhat Abbes University of Sétif including 15 participants who tested the 3DVL@ES before confinement and 15 others during confinement. 60.03% of the participants are female and 31.97% are male. Learners who participated are in their first year of a Master's chemistry degree. All learners have already participated in traditional labs. 75% of the participants had never used virtual labs before. The evaluation of the proposed virtual laboratory consists of three main phases: pre-lab, lab, and post-lab. Each phase is composed of successive steps.

- **Pre-Lab:** during the first phase, a set of worksheets and documentation (video) are presented to identify the lab requirements. The learner starts to explore the 3D virtual lab and simulates random trials to well understand and familiarize with the lab.
- **Lab:** during this phase, learners realize practical works individually. The collaborative practical work is achieved more adequately in the following steps: (1) - establishing the connection with learners in the same group and (2) - working collaboratively.
- **Post-Lab:** the communication and document-sharing tool made it easy to submit the results report and share the obtained results.
- After experimenting with the proposed virtual laboratory, we asked participants to answer the questions shown in Appendix A.

Experimental Results

The findings of this study after collecting results of the different questionnaires at the end of their practical works are encouraging as shown in Figure 14. Two different evaluations were used to assess the result according to different parts: user interface, individual interaction, and collaboration

- The user interface: The evaluation results show that all participants were able to access the virtual environment and start working. They indicate that the environment is easy to use, and 3D objects are easily accessible. In addition, they felt free to work in this environment. However, the average time needed to get familiar with the environment is 5 minutes. 95% of participants are satisfied with the user interface. 80% of the participants have never used such an environment. The user interface is considered easy, visible, and accessible.
- Individual interaction: 75% of participants can work on our environment, select objects, move objects, and even do comfortably the steps of practical work. The average response time for completing the course was 20 minutes.
- Collaboration part: Participants are divided into two groups who are logged to work collaboratively. The experimental results show that all participants are satisfied with the communication tool and

shared different documents. For the realization of the project, 13% of participants could not work together. This result is expected, and this is due to internet connection for sharing the working space. It was too difficult to make 3D rendering in real-time. 55% of participants satisfyingly finished the project.

3DVL@ES is compared with two other free virtual laboratories mentioned in the related work section: Praxilabs (https://praxilabs.com/) and PhET (https://phet.colorado.edu/).

- Praxilabs is a three-dimensional lab specialized in experimental sciences (*physics, chemistry, and biology*). Figure 15.a shows the Praxilabs main interface
- PhET is a virtual environment for interactive and independent simulations (2D and 3D) in the field of mathematics and experimental sciences (Figure 15.b). Access to this environment is done online through the website or offline by installing the application on a computer.

Figure 16 compares the *evaluation results of* 3DVL@ES and Praxilabs. All learners can easily access Praxilabs and find the interface simple and user-friendly. 3D objects can be used to represent real objects. However, we noticed that they are uncomfortable when using Praxilabs. When the learner selects objects to perform tasks, Praxilabs laboratory is ready on the workbench automatically and he cannot make up random interactions. Praxilabs laboratory provides already programmed simulations with predefined actions. The laboratory suffers from the total absence of collaboration, for both interaction and communication side.

Figure 17 compares the evaluation results of 3DVL@ES and PhET. All learners can access the PhET interface and select the right practical simulation. The objects are well reflected real objects. Learners selected objects randomly and interacted freely but did not have a sense of immersion while handling and interacting with the environment. However, learners cannot find a way to work together (collaboration, communication, and collaborative interaction). They feel that is not a real environment that motivates practical learning. Further, it lacks an explanation of concepts studied in the theoretical courses.

We evaluated the learner within 3DVL@ES in terms of eight criteria: critical thinking, disability, physical activities, interactivity, behavior and social communication, performance on tasks, understandability, and practical work outcome using the Daniell Cell case study. To do so, we consider 21 learners of sciences faculty of SETIF-1university. These learners realize Daniell Cell according to pedagogical interaction models for each group of learners. Figure 18 shows the average percentage with a group of learners.

Figure 15. a) Praxilabs main interface b) PhET main website interface

-a-   -b-

Figure 16. Comparison between the evaluation results of 3DVL@ES and Praxilabs
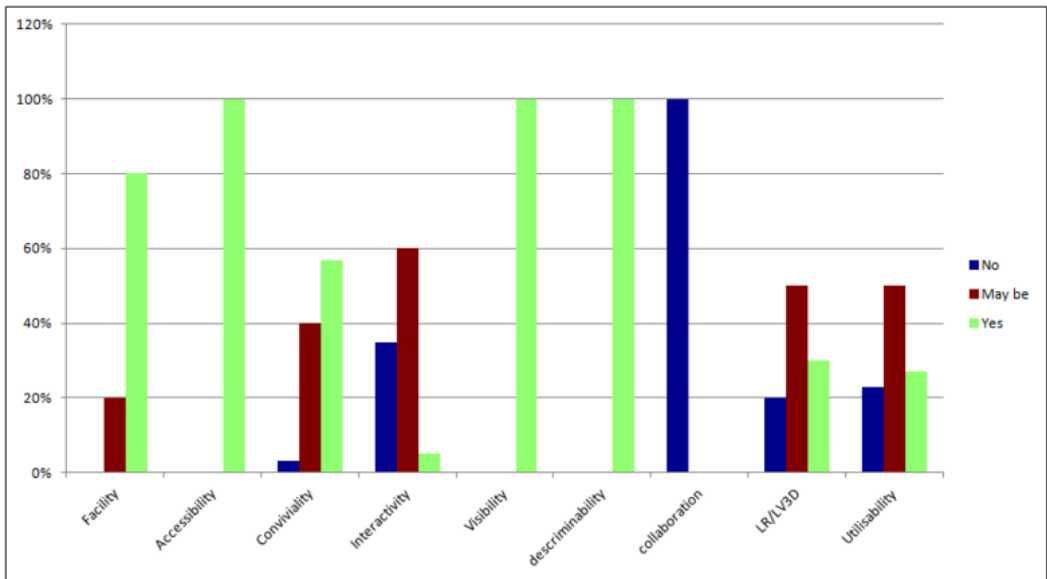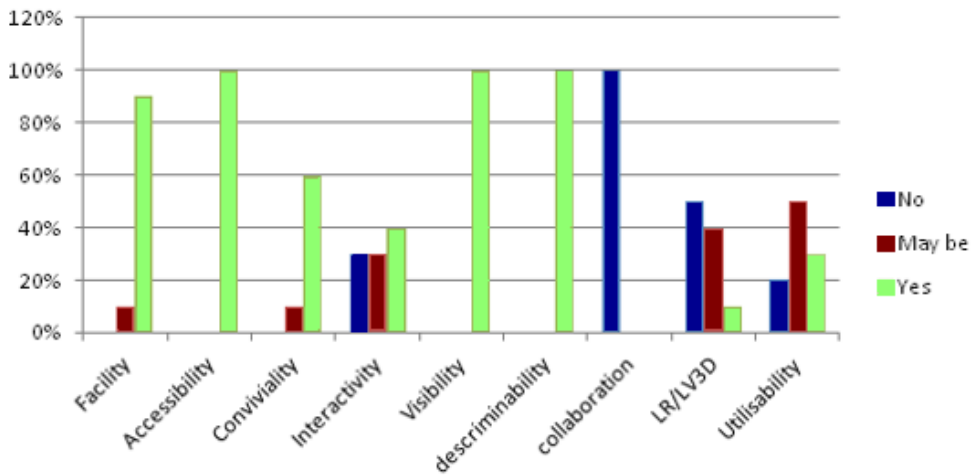

**Figure 17. Comparison between the evaluation results of 3DVL@ES and PhET**

According to results in Figure 18, 3DVL@ES virtual lab shows good interactivity with 73.01%, understandability 75%, behavioral and social communication 75% and practical work outcome 66.66%. The reason goes to the introduction of virtual collaborative pedagogical interactions as well as understandability and social communication than other traditional laboratories such as PhET and Praxilabs.

DISCUSSION

The conducted experiments highlight how the application of 3DVL@ES leads to enhancing the effectiveness and ease of development of labs. Specifically, the following benefits and goals can be achieved by the 3DVL@ES adoption:

Figure 18. Global evaluation of 3DVL@ES
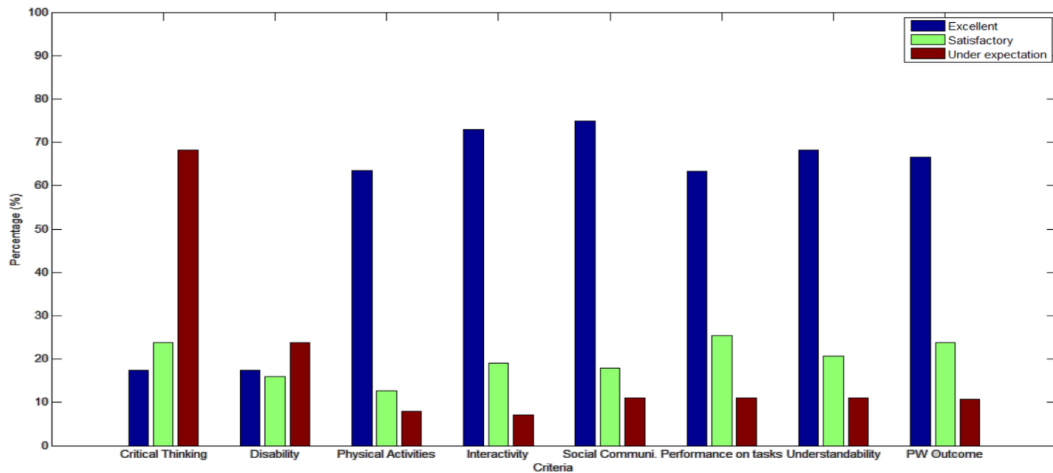
- Improved quality of distance learning practical work because of collaboration, social interaction, and learner engagement and intents.
- Reduction of the required effort and time.
- Improved cooperation between learner teams, which is supported by the 3D web application automation and collaborative tasks provided by 3DVL@ES

Figures 16, 17 and 18 show that 3DVL@ES virtual lab promotes better interactivity over other virtual laboratories PhET and Praxilabs on case study of Daniell Cell by a difference of 45% and 35% respectively. The improvement of facility can be observed with a difference of 45% between 3DVL@ES and PhET and a difference of 2.5% between 3DVL@ES and Praxilabs.

The experiments on a case study of Daniell cell show that the 3DVL@ES virtual laboratory in collaborative learning provides good performance results compared to other virtual laboratories Praxilabs and PhET. This is due to the various interaction's techniques of 3DVL@ES with an effective collaborative learning process. The 3DVL@ES virtual lab outperforms the interactive simulator, PhET and 3D virtual laboratory Praxilabs applied on case study of Daniell Cell in terms of achievement time, which is 1.679 seconds. This is due to simultaneous and collaborative interaction actions.

The limitations that we faced during the development stages of the virtual laboratory were those of online communication. Absence of efficient evaluation strategy for assessing learners' practical works. Possibilities of developing 3D immersive web-based virtual reality applications needed much effort. Moreover, not being able to extract automatically relevant actions from the worksheet in the online mode also affected the automatic generation of interaction tasks in some ways.

CONCLUSION

The paper has introduced 3DVL@ES a 3D Web-based virtual laboratory for assisting learners to efficiently perform practical work and organize document exchanges between them within a shared virtual space. To be able effectively to support the design process, such 3DVL@ES has been found in the remote collaboration and cooperative tasks of practical labs. According to these principles, incremental methods have been used in order to enable designers to 1) create and generate 3D web-based educational applications and 2) –add collaborative and interaction aspects in defining complex interactions on the unified application model. 3DVL@ES lab has been evaluated using a case study

of Daniell cell. Finally, we distributed a questionnaire (comparing 3DVL@ES to two virtual labs available for access freely) to potential learners and collected their responses. The obtained results in figures 14-15 show the superiority of 3DVL@ES compared to Praxilabs and PhET in terms of visibility, interactivity, and facility. However, the conducted experiments highlight how the application of 3DVL@ES leads to enhancing the effectiveness and ease of development of virtual laboratories. Specifically, the following benefits and goals can be achieved by the 3DVL@ES adoption: (1) improved quality of distance learning practical work because of collaboration, social interaction, and learner engagement and intents, (2) reduction of the required effort and time and (3) Improved cooperation between learner teams, which is supported by the 3D web application automation and collaborative tasks provided by 3DVL@ES The limitations that we faced during the development stages of the virtual laboratory were those of online communication. Absence of efficient evaluation strategy for assessing practical works of learners. Possibilities of developing 3D immersive web-based virtual reality applications needed much effort. In the future, we plan to achieve a full supporting lab and apply 3DVL@ES in all science faculties of our university.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare

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REFERENCES

Abramov, V., Kugurakova, V., Rizvanov, A., Abramskiy, M., Manakhov, N., Evstafiev, M., & Ivanov, D. (2017). Virtual biotechnological lab development. *BioNanoScience*, 7(2), 363–365. doi:10.1007/s12668-016-0368-9

Astutik, S., & Prahani, B. K. (2018). The Practicality and Effectiveness of Collaborative Creativity Learning (CCL) Model by Using PhET Simulation to Increase Students' Scientific Creativity. *International Journal of Instruction, 11*(4), 409-424.

El Kharki, K. Berrada, K. Burgos, D. (2021). Design and Implementation of a Virtual Laboratory for Physics Subjects in Moroccan Universities. Sustainability, 13(7), 3711. doi:10.12973/iji.2018.11426a

August, S. E., Hammers, M. L., Murphy, D. B., Neyer, A., Gueye, P., & Thames, R. Q. (2016). Virtual engineering sciences learning lab: Giving STEM education a second life. *IEEE Transactions on Learning Technologies*, 9(1), 18–3. doi:10.1109/TLT.2015.2419253

Bach, C., & Scapin, D. (2005). *Critères Ergonomiques pour les Interactions Homme-Environnements Virtuels: définitions, justifications et exemples* [Doctoral dissertation]. INRIA.

Bogusevschi, D., & Muntean, G. M. (2019). Virtual Reality and Virtual Lab-Based Technology-Enhanced Learning in Primary School Physics. In *International Conference on Computer Supported Education* (pp. 467-478). Springer.

Broisin, J., Venant, R., & Vidal, P. (2017). Lab4CE: a remote laboratory for computer education. *International Journal of Artificial Intelligence in Education, 27*(1), 154-180. 10.1007/s40593-015-0079-3

Correia, A. P., Koehler, N., Thompson, A., & Phye, G. (2019). The application of PhET simulation to teach gas behavior on the submicroscopic level: Secondary school students' perceptions. *Research in Science & Technological Education*, 37(2), 193–217. doi:10.1080/02635143.2018.1487834

El Kharki, K., Berrada, K., & Burgos, D. (2021). Design and Implementation of a Virtual Laboratory for Physics Subjects in Moroccan Universities. *Sustainability*, 13(7), 3711. doi:10.3390/su13073711

El Kharki, K., Berrada, K., Bensamka, F., Hajjaji, K., El Kbiach, M., & Bounab, L. (2018). Vers un laboratoire virtuel des TP en Sciences physiques: cas du projet EXPERES. *International Journal of Applied Research and Technology*. http://www.IJARTech.com

El Kharki, K., Bensamka, F., & Berrada, K. (2020). Enhancing practical work in physics using virtual javascript simulation and LMS platform. In *Radical solutions and eLearning* (pp. 131–146). Springer. doi:10.1007/978-981-15-4952-6_9

Kolil, V. K., Muthupalani, S., & Achuthan, K. (2020). Virtual experimental platforms in chemistry laboratory education and its impact on experimental self-efficacy. *International Journal of Educational Technology in Higher Education*, 17(1), 1–22. doi:10.1186/s41239-020-00204-3

Gardner, A., Duprez, W., Stauffer, S., Ungu, D. A. K., & Clauson-Kaas, F. (2019). *Labster Virtual Lab Experiments: Basic Biochemistry*. Springer Berlin Heidelberg. doi:10.1007/978-3-662-58499-6

Gardner, A., Stauffer, S., Petley-Ragan, L., Wismer, P., & Ungu, D. A. K. (2019). *Labster Virtual Lab Experiments: Genetics of Human Diseases*. Springer Berlin Heidelberg.

Mechta, D., Harous, S., Djoudi, M., & Douar, A. (2012). Supervision and Control Tool for Collaborative Virtual L@ boratory. *Journal of Software*, 7(7), 1496–1504. doi:10.4304/jsw.7.7.1496-1504

Mellos Carlos, L., Schardosim Simão, J. P., Saliah-Hassane, H., Silva, J. B. D., & Mota Alves, J. B. D. (2019). Design and Implementation of an Architecture for Hybrid Labs. In *International Conference on Remote Engineering and Virtual Instrumentation* (pp. 123-142). Springer. doi:10.1007/978-3-030-23162-0_13

Mostefaoui, H., Benachenhou, A., & Benattia, A. A. (2017). Design of a low cost remote electronic laboratory suitable for low bandwidth connection. *Computer Applications in Engineering Education*, 25(3), 480–488. doi:10.1002/cae.21815

Niandou, H., Mouton, S., Ballu, A., Blanchard, A., Michenaud, C., & Yan, X. (2017). Un Laboratoire Virtuel pour Moodle. In *CFM 2017-23ème Congrès Français de Mécanique*. AFM.

Praxilabs 3D Virtual Lab Simulations. (2021). Sciences/Praxilabs, https://praxilabs.com/

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, *95*, 309–327. doi:10.1016/j.compedu.2016.02.002

Radhamani, R., Kumar, R., Nizar, D., Achuthan, N., Nair, K. B., & Diwakar, S. (2021). What virtual laboratory usage tells us about laboratory skill education pre- and post-COVID-19: Focus on usage, behavior, intention, and adoption? *Education and Information Technologies*, *26*(6), 1–19. doi:10.1007/s10639-021-10583-3 PMID:34121909

Rice, W. (2015). *Moodle e-learning course development*. Packt Publishing Ltd.

Salame, I. I., & Samson, D. (2019). Examining the Implementation of PhET Simulations into General Chemistry Laboratory. *International Journal of Environmental and Science Education*, *14*(4), 207–217.

Salame, I. I., & Makki, J. (2021). Examining the Use of PhET Simulations on Students' Attitudes and Learning in General Chemistry II. *Interdisciplinary Journal of Environmental and Science Education*, *17*(4), e2247. doi:10.21601/ijese/10966

Saslow, W. M. (1999). Voltaic cells for physicists: Two surface pumps and an internal resistance. *American Journal of Physics*, *67*(7), 574–583. doi:10.1119/1.19327

Stahre Wästberg, B., Eriksson, T., Karlsson, G., Sunnerstam, M., Axelsson, M., & Billger, M. (2019). Design considerations for virtual laboratories: A comparative study of two virtual laboratories for learning about gas solubility and colour appearance. *Education and Information Technologies, 24*(3), 2059-2080. doi: 10.1007/s10639-018-09857-0

Stauffer, S., Gardner, A., Ungu, D. A. K., López-Córdoba, A., & Heim, M. (2018). *Labster Virtual Lab Experiments: Basic Biology*. Springer.

Sarrazin, J., Verdaguer, M. (1998). L'Oxydoréduction concepts et expériences. *Ellipses*.

Wahyono, I. D., Putranto, H., Saryono, D., & Asfani, K. (2020). Development of a Personalized Virtual Laboratory Using Artificial Intelligent. In *International Conference on Learning Innovation 2019 (ICLI 2019)* (pp. 101-107). Atlantis Press. doi:10.2991/assehr.k.200711.018

APPENDIX

Evaluation of the 3DVL@ES, Praxilabs sand PhET virtual laboratories
For each question, three possible answers were available (Yes, May be, No)

Table 4. Evaluation of the 3DVL@ES, Praxilabs sand PhET virtual laboratories

No.	Question	Yes	Maybe	No
1	Do you generally find the VL easy to use?			
2	Are 3D Virtual Objects accessible in a minimum of time/action?			
3	Do you find the VL interface user-friendly?			
4	Do you feel comfortable working in this environment?			
5	Did the interface have the capacity to offer the set of actions you want to perform to complete the task?			
6	Do you think that the VL allows you to easily manage complex interactions (*collaborative pedagogical interactions, sharing of documents*)			
7	Do you find that the objects are well organized, and seen from various perspectives?			
8	Do you find that the practical room is well visualized in the VL?			
9	Can you easily distinguish virtual objects from each other			
10	How do you find the collaborative work between you and your colleague in VL?			
11	How do you find communication with your colleague?			
12	Do you think that the objects are well modeled the real tools of PW?			
13	Do you think that the VL can be used for learning the practical exercises?			
14	Do you think the collaborative space was beneficial?			

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