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PAPER

Effectiveness of Virtual Labs for Physics Learning in Moroccan Secondary Schools

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ABSTRACT

The teaching of physical sciences primarily relies on the use of experimental activities to explain the phenomena and physical concepts taught theoretically in class. Nevertheless, this conventional approach faces various challenges and problems, which limit its ability to achieve the different pedagogical objectives set by teachers. In this study, we evaluated the effectiveness of virtual laboratories ("VLABs") as an alternative tool to traditional practices for teaching physics concepts in Moroccan secondary schools. The methodology followed in this study is quantitative and based on two questionnaires. The first is intended for teachers to evaluate the experimental activities on VLABs based on a socio-technical and pedagogical heuristic study and to verify their conformity with the expectations and characteristics of each type of learner according to the Felder-Silverman learning style preferences. The second was administered in the form of an evaluation to compare the performance of the control group with the experimental group that integrated the opportunities offered by the VLAB LABSTER. The results show that VLABs are not only comparable to conventional experimental activities in terms of applicability, ease of use, and effectiveness in achieving the learning objectives for which they were initially designated but surpass them in terms of performance, as evidenced by the significant improvement of the mean obtained by the group that integrated the experimental activities on the VLAB. Thus, VLABs can be used not only as an alternative to traditional experimental activities in distance learning but also as a viable option for potential adoption even in traditional face-to-face physics instruction.

KEYWORDS

virtual labs (VLABs), augmented reality (AR), virtual reality (VR), experimental activities, physics learning, quantitative evaluation

1 INTRODUCTION

Science learning is based on an experimental approach that emphasizes the development of analytical and problem-solving skills. Learners are encouraged to conduct experiments, collect and analyze data, interpret results, formulate hypotheses,

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and draw conclusions based on scientific evidence to be able to understand and explain natural phenomena, as well as apply scientific principles to solve everyday problems and societal challenges [1–4]. Since it is based on abstract scientific concepts, physics requires observation, imagination, reflection, and experimentation. Thus, conventional learning approaches may prove less advantageous at times, either due to their reliance on intricate and unfeasible experiments conducted in real-world scenarios, given the scarcity of scientific resources in laboratories, or the inadequacy of fundamental and ongoing training in experimental activities [5–7].

After the COVID-19 crisis, distance learning has become essential for the states to not only continue the educational offer in times of emergency but also to leverage these advantages to innovate new sustainable teaching methods. The experience of this crisis has shown that courses can be continued in different ways [8–10]. However, in the Moroccan secondary schools, the experimental activities were, in the majority of cases, suspended or rarely carried out in the form of explanatory videos [11]. Therefore, these activities initially designated to facilitate the assimilation of abstract scientific concepts may be a factor limiting this understanding [12], [13].

Nowadays, technological advancement is progressing rapidly and seems far from being completed. Indeed, technologies play a crucial role in our lives, especially in the field of education. The integration of new technologies in schools offers various possibilities to make the teaching-learning process more enjoyable and effective in maintaining the engagement, involvement, and motivation of learners. This is because the various disciplines taught inherently involve a diversity of knowledge, skills, attitudes, abilities, and competencies that need to be developed in the learner. This requires a good adaptation to this evolution to enhance the quality of the training services provided and overcome the challenges of traditional teaching methods in general, and more specifically in fields based on experimental approaches such as physics.

One of the manifestations of new technologies that have recently taken over the world is virtual reality (VR) and augmented reality (AR) technologies. These technologies are currently emerging as a significant choice for learning tools in the field of education, and several countries have adopted their use. They are powerful visualization tools capable of leveraging components of the human nervous system and guiding learners through complex cognitive tasks. Which is crucial in the learning process of various scientific disciplines. Virtual laboratories (VLABs) based on VR and AR offer the advantages of unlimited time, immediate feedback, experiment repetition, and safety for students and experimental subjects. [11].

Recently, several research papers have studied the application of VLABs in various fields to address the limitations preventing traditional experimental activities from achieving their goals: [14], [15] in the field of chemistry, [16] examined the effectiveness of VLABs in the field of computer science, and [17] in medicine.

In the field of physics, according to [18–21], students who received instruction using a VLAB achieved better results on assessments of conceptual knowledge and more rapidly improved their ability to use authentic equipment. [22] asserts the improvement in the level of conceptual knowledge of Rwandan students in the experimental group who used the VLAB compared to students in the control group.

The study of these state-of-the-art methods demonstrates that they are either limited to a specific country, requiring verification of results in a different context, or focus on the direct effect of using VLABs on student understanding without considering the issues related to VLAB usage and each student's learning preferences. In order to overcome these limitations, the objectives of this article are to:

- Check the effectiveness of VLABs for teaching physics concepts in Moroccan secondary schools.
- Evaluate the problems related to accessibility and use of VLABs based on a socio-technical and pedagogical heuristic method;
- Ensure that VALBs comply with the expectations and characteristics of each type of student according to the Felder-Silverman learning style preferences concept;
- Explore the advantages of experimental activities based on VR and AR and their contribution to improving the effectiveness of distance learning to identify potential limitations of these technologies and study future improvement prospects.

The remainder of this paper is organized as follows: The literature review is presented in Section 2. Section 3 describes the method followed to carry out this study, the instruments used, and the data collection and processing procedure. The results obtained are explicitly presented and discussed in Sections 4 and 5, whereas the conclusions of this work are presented in Section 6.

2 LITERATURE REVIEW

2.1 Virtual labs

Since the onset of the 21st century, incorporating new technologies into our daily lives has become indispensable. This widespread use is prompted by the swift evolution of these technologies in terms of hardware (PCs, tablets, mobile phones, etc.) and software (operating systems, mobile applications, 2D and 3D modeling, artificial intelligence, etc.) [23]. VR and AR are among these emerging technologies used in various fields, and education is not exempt from their utilization [14], [15], and [24]. Virtual labs are one of the important applications of these technologies in education. A VLAB serves as a simulation tool, enabling the representation of a real phenomenon within a virtual environment [25]. It provides a computer environment that can be accessed remotely, allowing flexibility in time (available at any moment) and space (from home or at school). It is easily compatible with hardware such as laptops, tablets, or mobile phones [25].

In recent times, numerous studies have highlighted the benefits of incorporating VLABs across different fields. In the medical domain, for instance, VLABs offer the capability to model the human body, providing access to previously inaccessible areas without the associated risks to human life, time, or space. [26–28]. In the field of biology, VLABs grant access to costly instruments such as microscopes, facilitating safe experimentation and measurements such as radioactivity measurement or cell stimulation [29–31]. In the realm of chemistry, VLABs enable the real-time observation of chemical reactions and the manipulation of molecules in three dimensions without the associated risks, such as explosions. Examples include the reaction of sodium (Na) with water and the release of toxic gases such as hydrogen chloride (HCl), hydrogen cyanide (HCN), and carbon monoxide (CO) [32].

In the Moroccan context, several articles have studied the use of VLABs in education [33], in the field of biology. [34], in the field of chemistry. Regarding the teaching of physics, few papers discuss the use of this technology at advanced levels, such as university [35] and engineering education [36].

2.2 Importance of experimental activities in physics

Physics is a branch of science that focuses on the study of natural phenomena. The diversity of its phenomena can be challenging for many students to grasp.

Some studies have concluded that these difficulties are linked to the complexity of the material itself, which is based on the following process: a) Understanding the studied physical phenomenon and connecting it with theoretical concepts that model the physical world; b) Mapping these concepts in the form of abstract mathematical models to reach calculated conclusions; c) Reframing the obtained results and relating them to the physical phenomena studied in nature through real experiments [37], [38].

Other studies [5], [10], [12], and [13] have concluded that the problem of understanding physics is attributed to traditional teaching methods that struggle to make the abstract concepts of physics concrete and tangible for students. This can lead to a gap between the theory taught in the classroom and its practical application in real life.

In the realm of physics education, Morocco faces similar challenges, as highlighted in international reports. The country's standing in assessments such as the 2015 International Association for the Evaluation of Educational Achievement (IAE) and the TIMSS assessments in 2011, 2015, and 2019 has raised concerns [39].

By contributing to the evidence presented in previous studies, which demonstrates the effectiveness of VLABs in modeling various real-world phenomena to enhance comprehension across diverse fields and to address the challenges hindering physics education in Morocco by providing access to experimental activities and 3D modeling anytime, anywhere, our study seeks to examine the efficiency of VLABs in teaching physics concepts in Moroccan secondary education. Additionally, we aim to evaluate the problems related to the accessibility and use of VLABs and to ensure that VALBs comply with the expectations and characteristics of each type of student according to the Felder-Silverman learning style preferences concept, as well as define potential limitations of these technologies to study future improvement prospects.

3 METHOD

3.1 Research procedure

To meet the predetermined objectives, this study relies on two questionnaires. The first one is addressed to secondary school teachers in Morocco, aiming to evaluate the experimental activity on the VLAB LABSTER.

The second one was conducted as a comparative test between two baccalaureate-level classes that have never studied the chosen physical concept: "Electrostatics: Coulomb's Law." One class was randomly selected to attend a 30-minute theoretical lesson delivered through a PowerPoint presentation and perform a 15-minute experimental activity using the VLAB LABSTER. The second class served as the comparative group "Control Group," which attended the same theoretical course Material and received an explanation of the experimental activity through a video.

The first survey was sent to 20 secondary school teachers in the Rabat-SALE region of Morocco. The second one involved a total of 76 students, divided into two groups of 38 students each.

To ensure the reliability of this study, the research protocol and procedure were overseen and verified by the Higher School of Education and Training. The use of an electronic survey for data collection ensures respondent privacy, with measures in place to mitigate the social desire effect, in line with recommendations from [40–43]. The surveys emphasize the importance of authentic responses, ethical dedication, and acknowledgment of the significance of sincere answers in addressing the problems, challenges, and opportunities they are experiencing.

3.2 Instruments

To conduct this study, we used two questionnaires. The first one is designed to evaluate the experimental activity on the VLAB LABSTER, as described in Figure 1. This evaluation is conducted based on a socio-technical and pedagogical heuristic study. This method has been selected due to the widespread utilization of heuristics across diverse domains, including software development, marketing, and human-computer interaction. Heuristics function as a checklist or a rule of thumb to pinpoint significant issues and challenges within digital systems, primarily focusing on the user's interaction with the technology [44] (refer to Table 1). Furthermore, this survey aims to ensure that VALBs comply with the expectations and characteristics of each type of student according to the Felder-Silverman learning style preferences concept. We opted for this model because it is highly prevalent in technology-enhanced learning, primarily due to its capacity to measure how students perceive, process, comprehend, and retain information [45] (refer to Table 2).

The questionnaire for students comprises ten "10" questions, with the first five assessing the theoretical aspect (basic questions Q1, Q2, Q3; advanced questions Q4 and Q5) and the last five evaluating the practical component (basic questions Q6, Q7, Q8; advanced questions Q9 and Q10).

We have chosen LABSTER because it provides students with an immersive virtual learning experience, allowing them to carry out realistic scientific experiments in a virtual environment [46]. Furthermore, this software offers an array of VLABs across diverse disciplines, including physics. Students can engage in simulations based on real-life scenarios in a secure environment, accessible anytime and from anywhere. All they need is a compatible VR headset (preferably to leverage the 3D features) and an internet connection, enabling them to practice scientific skills and deepen their understanding of key concepts at their own pace [47].

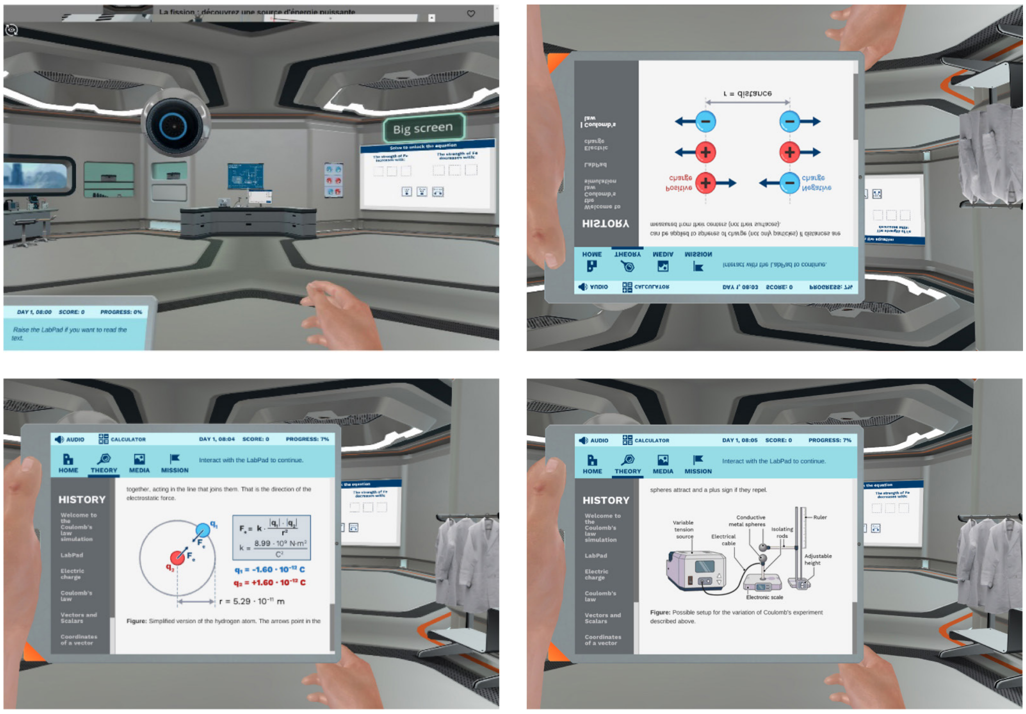

Fig. 1. Display of experiments on the VLAB (LABSTER)

Table 1. 14 Socio-technical and pedagogical heuristics [44]

N°	Heuristics	Type	Explanation
1	Social presence	Social	Possibility for learners to introduce themselves to the class.
2	Group activity	Social	Activities promote active reflection, collaboration, discussion, and real-world engagement.
3	Ease of use	Technology	It is easy to upload files.
4	Page layout	Technology	Links are easily recognizable.
5	Ecosystem	Technology	It provides access to all the resources necessary to support effective learning.
6	Navigation	Technology	Design enables learners to easily locate where they are within the course.
7	Functionality	Technology	The technology works consistently and reliably.
8	Accessibility	Technology	Images and graphics contain alt text or descriptive captions.
9	Quality	Pedagogical	Various forms of media are included for remediation and/or enrichment.
10	Organization	Pedagogical	For blended learning, instructions make clear which materials are to be used in the face-to-face classroom and which are specific to the online portion of the course.
11	Assessment	Pedagogical	The teacher gives active, specific, and consistent feedback and feedforward to student learning progress.
12	Syllabus	Pedagogical	The syllabus communicates student expectations.
13	Learning Goals	Pedagogical	Learning objectives are stated clearly, and written from the student's perspective.
14	Guidance	Pedagogical	Instructor contact information for course questions is provided.

Table 2. Felder-Silverman learning preferences [45]

Felder-Silverman Learning Preferences	
Type of Learner	**Preferences**
Sensing	Prefers concrete thinking, practical, concerned with facts and procedures
Intuitive	Prefers conceptual thinking, innovative, concerned with theories and meanings
Visual	Prefers visual representations, pictures, diagrams, and flow charts
Verbal	Prefers written and spoken explanations
Active	Prefers to try things out, working with others in groups
Reflective	Prefers thinking through, working alone or with a familiar partner
Sequential	Prefers linear thinking, is orderly, learns in small incremental steps
Global	Prefers holistic thinking, systems thinkers learn in large leaps

4 FINDINGS

To address the research questions in this study, the findings are outlined in the following process:

- Results concerning the teachers: The first part illustrates a comparative socio-technical and pedagogical study between experimental activities based on videos or PDFs and those based on VLABs. The second one presents an assessment of VLAB's suitability to learners' preferences using the Felder-Silverman learning style preferences through a comparison of various types of experimental activities (conventional, video/PDF, and VLAB).

- Student-related results based on a comparison of outcomes between the test group that underwent the theoretical course and experimental activity on the VLAB LABSTER and the control group that followed the same theoretical course with an experimental activity presented through a video.

4.1 Procedure of data analysis

The results are organized and analyzed using Microsoft Excel. They are presented in statistical form, including percentages, averages, and standard deviations, following the categorization and grouping of responses from both teacher and student questionnaires. The objective of this analysis is to assess the effectiveness of VLABs in teaching physics concepts within Moroccan secondary schools and explore the benefits of experimental activities incorporating VR and AR and their role in enhancing the efficiency of distance learning. Furthermore, the analysis aims to identify potential limitations of these technologies to study prospects for improvement.

4.2 Heuristic socio-technical and pedagogical study

To compare the effectiveness of experimental activities based on video or PDF and those based on the VLABLABSTER, we consolidated the results from the teachers' questionnaire. The 20 teachers were asked to evaluate each type of experimental activity based on the 14 heuristics outlined and explained in Table 1. The assessment of each heuristic could be categorized as (no issues; minor issues; major issues; and not applicable).

For ease of result interpretation, responses are displayed through the graphs in Figure 2, comparing between:

- The percentages of answers indicate whether the type of activity has no issues or minor problems concerning each heuristic.
- The percentages of responses signaling that the type of activity is either not applicable or poses major problems compared to each heuristic.

Based on Figure 2, we can observe that:

- 100% of teachers perceive that VLABs and experimental activities through videos and PDFs enable:
  - Simple navigation within the content
  - Efficient operation of both technologies;
  - Clear presentation of the required syllabus;
  - Achievement of the initially designated learning objectives.
- Every instructor (100%) confirmed that VLABs effectively facilitate:
  - Social interaction among learners during the experimental activities;
  - Team collaboration among learners, encouraging cooperation and discussions throughout the execution of the experimental activities;
  - Resulting in the establishment of a learning and collaborative ecosystem among the learners.

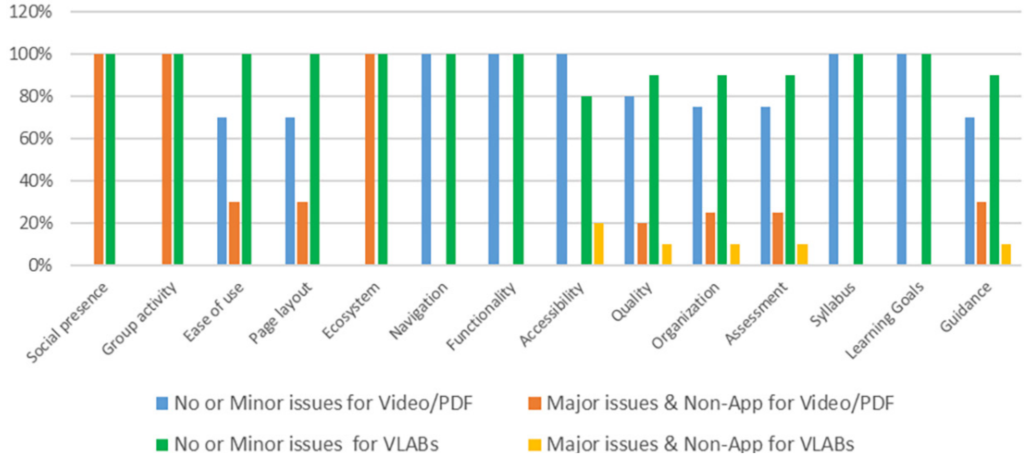

Fig. 2. Comparison of "No or Minor issues" with "Major issues or non-applicability" Results for Video/PDF and VLABs

- However, all teachers have affirmed that experimental activities through videos or PDFs are not applicable for these three heuristics (social presence, group activity, and ecosystem) since these types of activities are done individually and without any interaction.
- Every teacher (100%) has confirmed the user-friendly nature of VLABs, attributed to their simple and focused design, allowing for usage and reuse at one's convenience. However, 25% of teachers indicated encountering major issues with the usability and understanding of experimental activities presented in video or PDF formats.
- In terms of quality, organization, and ease of evaluation:
  - 90% of teachers reported no major issues with VLAB usage, while 10% faced significant challenges.
  - Approximately 70% to 75% of teachers didn't encounter major problems with the evaluation of experimental activities in video or PDF format, whereas 20% to 25% faced significant challenges.
- The only heuristic where the experimental activity in video or PDF outperforms that in the VLAB is accessibility, as indicated by 100% of responses reporting no issues for the former compared to 80% reporting no issues for the latter. This difference is understandable given the necessity of a VR headset to access the 3D features essential for maximizing the graphic performance of VLABs.

4.3 Study of compliance with the expectations and characteristics of each type of learner according to the learners' preferences of the Felder-Silverman concept

To assess the suitability of the VLAB LABSTER with the characteristics and expectations of each learner, teachers were invited to answer a questionnaire based on the eight learners' preferences according to the Felder-Silverman concept, as detailed in Table 2. This evaluation involved comparing the compliance of VLAB with both traditional experimental activities and those based on video or PDF.

To enhance result comprehension, teachers' answers have been analyzed and presented as percentages in the graph depicted in Figure 3:

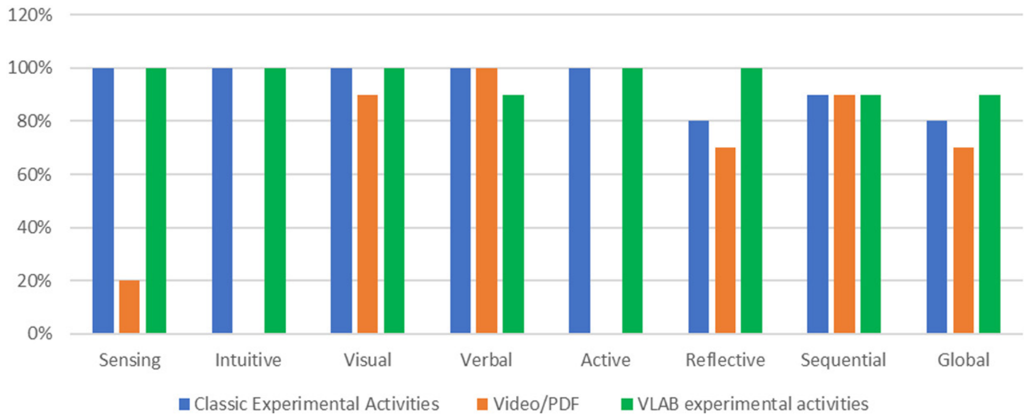

Fig. 3. Suitability of each kind of experimental activity with learners' characteristics according to Felder-Silverman preferences

Derived from Figure 3, it is evident that:

- All teachers recognize the high suitability of the VLAB for sensing, intuitive, visual, and active learners, aligning with the effectiveness of traditional in-person experimental activities. Nevertheless, less than 80% of teachers indicated that experiments explained in videos or PDFs are not suitable for these learner types.
- For sequential, reflective, and global learners, 90%, 100%, and 90% of teachers, respectively, affirmed the suitability of VLABs, whereas the percentage ranged between 80 and 90% for traditional experimental activities and was less than 80% for videos and PDFs.
- Regarding learners with a verbal preference, experimental activities explained in video or PDF, as well as traditional experimental activities, both surpass VLAB (90%) with a percentage of 100%. This is attributed to VLABs primarily relying on visual and practical effects rather than verbal explanations.

4.4 Results of the comparison between the learners' test and control groups

The test for students was conducted to quantify the effectiveness of experimental activities based on VLABs compared to those based on video or PDF on learners' understandings.

The level of knowledge assessment is compared between two groups of learners:

- The test group comprises 38 students who underwent the theoretical course on PowerPoint, followed by the experimental activity on the VLAB LABSTER.
- Control group: Another group of 38 students at the same academic level attended the same theoretical course on PowerPoint but followed an experimental activity presented in a video.

The test results have been consolidated in Table 3.

Table 3. Learners' test and control groups assessment findings

	Number of Students	Theoretical Mean	Practical Mean	General Mean	Standard Deviation
Control Group	38	6.89	5.69	12.57	3.26
Test Group	38	7.05	6.97	14.02	3.07

From Table 3, a noticeable improvement in the overall average of the test group, which performed the experimental activity on VLAB, is evident with an average of 14.02 and a standard deviation of 3.07 compared to the control group, which participated in a video-based experimental activity, with a general mean of 12.57 and a standard deviation of 3.26.

Further analysis of the average scores for the theoretical and practical sections in both groups reveals:

- The mean for the theoretical part is nearly the same: 6.89 for the control group and 7.05 for the test group.
- The average for the practical section is 5.69 for the control group and 6.97 for the test group. This indicates clearly that the significant difference in the overall average is attributed to the scores in the practical part. This suggests that learners who engaged in the VLAB experimental activity have a better grasp of the discussed physical concept compared to those who followed a video explanation of the experimental activity.

5 DISCUSSION

The results of this study, as presented above, have demonstrated that VLABs can effectively replace traditional experiments in distance learning. The sociotechnical and pedagogical heuristic-based approach has validated this effectiveness across the 14 heuristics where VLABs are applicable with either no issues or minor problems that do not compromise their overall efficiency. This is in comparison to the methods employed in Morocco for remote learning, which rely on simulations or explanations of physics experimental activities through videos or PDFs. This aligns with the findings in [44], which underscores the effectiveness of applying the 14 sociotechnical and pedagogical heuristics to the design of the VLAB learning experiences to detect potential major issues with their use in education.

Built upon VR and AR with 3D features, the VLAB allows all styles of learners, as per the Felder-Silverman preferences principle, to interact with experimental activities at any time and at their own pace. The strengths of the VLAB, including visual effects, virtual interaction, on-demand repetition, and the safety of conducting experimental activities without concerns about damaging equipment or posing risks to learners, make this technology not only an alternative to traditional experimental activities in distance learning but also an effective choice for potential adoption, even in traditional face-to-face physical science instruction. These outcomes are consistent with those in [47], which examined the benefits and positive effects of VLABs on students' performance in physics, taking into account their learning preferences.

The statistical analysis attesting to the effectiveness of VLABs was substantiated by the outcomes of the learner test group engaged in the experimental activity on the VLAB LABSTER. This group demonstrated a significantly higher overall average compared to the control group. The practical part's average indicated that conducting experiments on the VLAB LABSTER enabled learners to grasp the explained physical concept profoundly. The finding has shown an evident improvement, particularly in advanced-level questions requiring deep comprehension, analysis, and synthesis of the physical concept elucidated during the experimental activity. This level was not achievable for the majority of learners in the control group, as the experimental activity on video represents a passive process that hinders the immersive experience needed for a thorough understanding of the explained physical concept. This result confirms the findings of several previous studies. According to [21], students who received instruction using a VLAB obtained better results on assessments of conceptual knowledge and improved their ability to use authentic equipment more rapidly. [22] states that the level of conceptual knowledge among Rwandan students in the experimental group who used the VLAB was approximately 1.4 times higher than the level of conceptual knowledge achieved by students in the control group.

6 CONCLUSION

Teaching sciences in general, and particularly physics, relies primarily on experimental activities that elucidate the physical phenomena theoretically covered in classroom science courses. However, the traditional experimental approach encounters several challenges and issues within the Moroccan context, hindering its ability to achieve the originally envisioned outcomes [5].

In this study, VLABs were suggested as an alternative to the traditional approach applied in face-to-face learning, as well as to simulations and experimental activities through video or PDF during distance learning. The effectiveness of VLABs in teaching physics concepts in Moroccan secondary schools was examined. The results demonstrated a significant difference in the average scores between the group that performed the experimental activity on the VLAB LABSTER and the second group that attended the activity through a video.

In addition to the direct impact on learning physical concepts, VLABs have similar performance as traditional experimental activities in terms of applicability, ease of use, and efficiency in achieving the initially designated learning objectives. This has been evidenced by the results of the study based on the sociotechnical and pedagogical heuristic approach. The evaluation of VLABs' compliance with the characteristics and expectations of different learner preferences, based on the Felder-Silverman concept, has highlighted several other strengths.

Being based on VR, visual effects, virtual interaction, on-demand repetition, and the safety of conducting experimental activities without concerns about equipment damage or posing risks to learners, VLABs position themselves not only as an alternative to traditional experimental activities in distance learning but also as a viable option for potential adoption even in traditional face-to-face physical science instruction.

Expanding the scope of this work to include various countries and regions with different levels of development, taking into account a larger scale, and encompassing different types of online laboratories would allow us to comprehensively identify all factors influencing the integration of VLABs in teaching and learning and to offer a more thorough comprehension of the benefits and challenges associated with the use of this technology for learning in various contexts.

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