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Evaluation of the effects of a hybrid laboratory for learning a hardware description language: Insights into student motivation and academic performance

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Abstract

This research paper presents a study that investigates the effects of hybrid laboratories on learning Hardware Description Language (HDL) in digital electronics, focusing on student motivation and academic performance. With the advancement of telecommunications and computer applications in education, initiatives such as hybrid laboratories, which combine remote and on-site learning environments, have emerged. Despite this, the literature shows a lack of empirical evidence on the effect of these initiatives on students' learning process in digital electronics. To address this gap, this study implemented a hybrid laboratory and a quasi-experimental design with two groups: an experimental group and a control group. The experimental group used the hybrid laboratory while the control group practiced in a traditional physical lab. Student motivation was assessed through the MSLQ-Colombia questionnaire and a perception survey, while academic performance was measured through laboratory report grades. Quantitative results showed no significant improvements in learning motivation or academic performance in the experimental group. However, qualitative analysis revealed improvements in students' learning self-efficacy expectations, beliefs about control over learning, value of the task, autonomous learning, reduction of anxiety in the evaluation process, and confidence in experimentation among students in the experimental group. These qualitative findings provide insights for the design of new educational initiatives aimed at improving HDL learning environments.

Keywords: Hardware description language (HDL), Motivation in learning, Self-regulated learning, Hybrid laboratory, Digital electronics design learning

Introduction

The rapid proliferation of digital electronics, underpinned by the growing integration of Internet of Things (IoT) applications and innovative biometric wearables, has increased the demand for skilled personnel capable of designing and implementing advanced electronic devices (Ma & Soin, 2022). In particular, mastery of hardware description languages (HDLs), such as VHDL and Verilog, is a central aspect of this capability. These languages facilitate the design of complex electronic systems beyond traditional gate-level design. However, the distinctive characteristics and learning challenges associated with HDL, including its non-sequential nature and syntactic similarities to other programming languages, necessitate the implementation of a pedagogical approach that effectively integrates these tools into digital electronics curricula (Phadke & Kulkarni, 2017).

It is widely acknowledged that traditional laboratory experiences play a pivotal role in mastering HDL. Consequently, educational strategies have evolved to enhance student engagement and learning outcomes (Jiménez-Fernández et al., 2020). Laboratory-based learning, especially in STEM disciplines, is instrumental in promoting experiential learning, integrating theoretical knowledge with practical application, and fostering essential psychomotor and cognitive skills (Mohsen et al., 2019). Moreover, such environments not only facilitate the development of skills, but also enhance motivation and collaborative problem-solving abilities (Abdulwahed, 2010).

Emerging from traditional laboratories (TLs), which are entirely on-site, and non-traditional laboratories (NTLs), which include remote and virtual settings, are hybrid laboratories (HLs). In essence, HLs combine the benefits of both traditional laboratories and non-traditional laboratories, providing a versatile learning environment that can adapt to diverse educational needs and scenarios (Brinson, 2015; Velosa, 2020). Studies on NTLs have demonstrated their value in increasing access and enhancing learning experiences in various domains, including electrical engineering (AbuShanab et al., 2018; Bowden et al., 2019; Mayoof et al., 2021; Winzker & Schwandt, 2019). However, there is a limited amount of research on the impact of NTLs. Most studies have focused on the technical aspects of creating such labs, but there is a lack of research on specific aspects of the learning process, such as student motivation and academic performance. In addition, data collection is often based on participant surveys, which limits the depth of insight into learning processes (Lei et al., 2018; Son et al., 2016; Szőke et al., 2022).

This study addresses the need for empirical research on the specific effects of hybrid laboratories on students' motivation to learn HDLs and their academic performance. To this end, it integrates both traditional and non-traditional laboratories. The research is based on the theoretical framework of self-regulation in learning, which is conceptualized as the process through which learners assume responsibility for directing and monitoring their own knowledge acquisition, establishing objectives, and evaluating their progress in achieving those objectives (Duckworth et al., 2019; Zimmerman, 2002). This framework encompasses both cognitive processes, such as the utilization of learning strategies, and motivational and affective dimensions. Consequently, it offers a more comprehensive understanding of college student learning (Pintrich, 2004; Pintrich & De Groot, 1990; Zimmerman, 2000).

In order to justify the emphasis on motivation in this study, it is essential to acknowledge that contemporary learning theories have evolved beyond the information processing paradigm (cognitive processes) to encompass the more encompassing self-regulated learning (SRL) model (Pintrich, 2004). The SRL model offers a more comprehensive understanding of motivation, integrating essential elements such as self-efficacy, control of learning, and emotional regulation (Pintrich, 2000). These components are of critical importance, as students' capacity to regulate their motivation directly impacts their persistence and adaptability in overcoming academic challenges (Weiner, 1986). In this study, motivation in learning was assessed using the Motivated Strategies Learning Questionnaire (MSLQ-Colombia), which was adapted by Ramírez-Echeverry et al. (2016) and has demonstrated construct validity and reliability in the context of this research. Moreover, academic performance was evaluated through the assessment of students' grades in the summative assessments of various course activities.

The central research question of this investigation is as follows: What are the effects of a hybrid laboratory on students' motivation to learn HDL and their academic performance in a digital electronics course? To address this, the study incorporates key motivational constructs, including intrinsic and extrinsic motivation, task value, beliefs about control of learning, self-efficacy expectations for achievement and learning, and anxiety. The significance of these subdimensions of SRL has been extensively documented in the literature. For example, self-efficacy has been demonstrated to exert a considerable influence on academic performance and engagement (Pintrich & Schunk, 2002). Moreover, these constructs facilitate a more comprehensive understanding of the relationship between students' beliefs about their capabilities and control over learning, and their academic outcomes (Schunk & Ertmer, 2000). This study employs a quasi-experimental design, thereby contributing insights to the field of engineering education. This research offers a comprehensive evaluation of how hybrid learning environments can foster student motivation and improve learning outcomes in engineering courses.

Conceptual framework

Motivation in learning

Motivation is recognized as a key driver of human behavior. It links goals and behaviors and drives the actions a person takes to achieve goals and satisfy specific needs (Redondo

& Martín, 2015). In addition, motivation and its components also regulate learning processes. Motivation to learn has been defined as "what encourages or drives learners to freely devote their time to a specific academic activity. It encourages learners not only to initiate the activity but also to continue working on it throughout their lives. These reasons are personal and different in each individual context, and they can come from the learners themselves or from external stimuli." (Filgona et al., 2020, p. 20). Therefore, it can be understood as a complex construct. In the model of self-regulation of learning, it includes various elements that interact and mediate with other dimensions such as self-regulation and effective learning. For example, a student who sets goals and adapts their strategies and skills to learning demonstrates a good self-regulation process, which requires an adequate level of motivation to learn (Pintrich & De Groot, 1990).

In general contexts, according to Expectancy-Value Theory, a person's level of motivation is derived from the relationship between the efficacy expectancy of an activity and the subjective value attached to it. This value can have an extrinsic focus, where the mental and physical effort invested is justified by the resulting gain from completing the activity, or an intrinsic focus, related to the well-being and enjoyment derived from performing the activity (Brown et al., 2015). In educational settings, students' efforts are directed toward achieving proposed academic goals, which are reinforced by various motivational components. Therefore, motivation is viewed as a key component that either facilitates or hinders student self-regulation (Duckworth et al., 2019). Motivational components can support the learning process by explaining students' beliefs and judgments when faced with the challenge of learning (Pintrich & De Groot, 1990). From the perspective of self-regulation in learning theory, these components are:

1. Intrinsic goal orientation: Refers to intrinsic reasons for engaging in learning activities, such as curiosity, a genuine desire to learn, or a sense of challenge in the task. This orientation stems from stimuli driven by an authentic inner impulse to learn.
2. Extrinsic goal orientation: Refers to extrinsic reasons such as grades, recognition, or scholarships, and the positive evaluation of others. This orientation is based on external stimuli from sources such as teachers or parents (Lin et al., 2017).
3. Task value: Involves the importance the student attaches to the task and whether it is useful and valuable to their learning process.
4. Learning control beliefs: Concerns the student's perception of personal control over their learning, or whether they believe it depends on external factors such as subject difficulty or teacher influence.
5. Self-efficacy performance expectations: Refers to the student's confidence and perceived ability to achieve good grades.
6. Self-efficacy learning expectations: Relates to the student's confidence and perceived ability to understand topics or successfully complete learning activities.

7. Anxiety: Refers to the worry or discomfort a student may feel during assessment processes.

In studies conducted in digital electronics learning contexts, innovations in laboratory practices have shown certain benefits in motivating students to learn. Properly designed and challenging laboratory tasks have significantly contributed to increasing intrinsic motivation to learn (Barak et al., 2016). In addition, it has been observed that the level of autonomous learning in this knowledge domain is associated with higher intrinsic motivation (Lin et al., 2017). Other studies have found that remote laboratory practices have generated additional motivation to continue experimenting (Abdulwahed, 2010). However, it is important to note that there are few studies that have specifically examined student motivation in HDL learning contexts.

Academic performance

Academic performance is generally an assessment that attempts to reflect a student's level of understanding of a subject, which is closely related to their ability to achieve the course objectives. This assessment is based on a comparison to a predetermined standard (Lamas, 2015). There are various measures associated with grades, such as grade point average, reports from teachers or parents, and even self-assessments by the student. It is important to note that these measures and standards can vary between countries, making direct comparisons difficult (Curcio et al., 2006). However, academic performance implies a relative comparison between the performance of students within the same group or unit (Rodríguez-Rosero et al., 2021).

Moreover, academic performance is also influenced by a student's self-regulation. For example, if a student does not manage distractions and allocate appropriate effort over time, their ability to complete tasks will be affected. In fact, academic performance can be influenced by motivation, as students may perceive learning as a cost-benefit relationship, evaluating the effort required to achieve learning goals, which are often aligned with academic performance. In this context, benefit is understood as the outcome reached (Ariza et al., 2018). Furthermore, a notable component of intrinsic motivation is associated with a deep learning approach. Thus, satisfaction with learning is higher and academic performance is likely to be better. In this way, motivation mediates the establishment of solid goals and efforts to achieve them in the learning process and academic performance.

Laboratory in learning

Laboratories are a key element of education in various fields of knowledge. Notably, a wide range of practices and experiments are used in science and engineering education with multiple benefits (Velosa, 2020). These include the acquisition of technical skills (Esposito et al., 2021), the integration of theory and practice that enhances reasoning and reflection, and the promotion of teamwork. In contrast to traditional lecture-only courses, laboratories allow students to learn from their mistakes (Almeida et al., 2022) and are one of the preferred options for experiential learning (Bhute et al., 2021). Moreover, laboratories can also play an important role in fostering motivation to learn (Jiménez-Fernández et al., 2020), as they influence students' goals and learning processes (Ma & Nickerson, 2006).

Different forms of learning laboratories can be classified based on the physical presence. As shown in Table 1, three main groups are distinguished: traditional laboratories (TLs), non-traditional laboratories (NTLs), and hybrid laboratories (HLs), the latter being the result of any combination of TL and NTL (Brinson, 2015; Velosa, 2020).

Each modality offers unique benefits. For instance, the TL promotes interaction between people, enhancing and fostering collaborative work (Viegas et al., 2018). Additionally, direct experience with the experiment provides individuals with a wealth of information about the environment and the nature of the phenomenon being studied (Brinson, 2015). However, TLs present challenges such as scalability, student safety (Szőke et al., 2022), and the need for trained personnel to supervise and use the equipment (Velosa, 2020).

On the other hand, NTLs are known for their flexibility of access and the availability of extended practice periods (Aitor et al., 2022). These laboratories allow for easier repetition of experiments and can be a viable option in emergencies, such as the COVID-19 pandemic in 2020 (Bhute et al., 2022).

HLs aim to take advantage of both TL and NTL modalities and integrate them appropriately into a single experiment. Their effectiveness, however, depends largely on the nature of the experiment and the learning context. For this reason, they can accommodate a range of student preferences and learning styles (Ma & Nickerson, 2006). Nevertheless, the benefits of HLs require further exploration. Therefore, research opportunities exist to better understand the various combinations of TL and NTL and their impact on learning (Brinson, 2015).

Table 1 Classification of labs according to the physical presence of a user and the equipment involved in an experiment. Adapted from Brinson (2015) and Velosa (2020)

Traditional labs – TL (or Hands-On, HO)	Non-traditional labs – NTL	
Traditional laboratories where students and equipment are in the same place. Involve a physical interaction for students with equipment placed on-site (face-to-face). Also known as Hands-On (HO) labs.	**Virtual lab - VL**	**Remote labs - RL**
	It is a simulation of the experiment. Results are delivered to users using a screen.	Equipment is positioned in a remote location. A user may access them through the Internet.
Hybrid labs - HL		
TL and NTL modalities can be combined to exploit the benefits of both. It may be all involved in a single experiment or in alternating modalities (flipped mode).		

In conclusion, laboratories remain a cornerstone of STEM education, promoting creativity, real-world application, and student engagement (Terkowsky et al., 2022). In digital electronics, the evolution has included components such as field-programmable gate arrays (FPGAs), which are used in both TL and NTL. These devices are versatile for digital design due to their flexibility and reconfigurability, allowing the development of digital circuits (Mohsen et al., 2019). To take advantage of them, HDLs such as Verilog and VHDL, are required (Magyari & Chen, 2021). NTLs initiatives based solely on simulation exist; however, remote initiatives that interact with physical devices have gained greater acceptance due to the higher realism they offer compared to simulations (Aitor et al., 2022). This is due to the frequent differences between simulation results and physical functionality (Materzok, 2019).

Establishment of a hybrid laboratory (TL or HO & RL integration)

The design of the hybrid laboratory, which integrates traditional lab (TL) and remote lab (RL) modalities, seeks to benefit student learning by promoting learner autonomy and flexibility. According to SRL theory, learner autonomy and control over the learning process are essential, and the hybrid model encourages these aspects by allowing flexible access to both physical and remote lab resources (Brinson, 2015; Zimmerman, 2002). Furthermore, remote labs provide greater accessibility and flexibility, allowing students to practice independently and more frequently, thereby improving learning outcomes (Viegas et al., 2018). This is consistent with the principles of blended learning, where the combination of traditional and remote methods has been shown to improve student engagement and learning by providing both immediate feedback and flexible, self-paced learning opportunities (Graham, 2006; Ma & Nickerson, 2006).

NTL remote lab selection

The hybrid laboratory (HL) used in this research was a combination of traditional (TL) and non-traditional (NTL) modalities, with the remote lab (RL) component playing a key role. To identify the most suitable remote lab, a comprehensive review of existing remote labs and their functionalities was conducted.

Initially, a systematic literature search was conducted for remote labs focusing on digital electronics, covering studies from 2012 onwards. This time frame was selected to ensure the use of up-to-date technologies capable of interacting with current equipment. As a result of this initial search, 300 articles mentioning or using RLs were identified.

Subsequently, the articles were filtered by reviewing their titles and abstracts, aiming to identify specific RLs and their functionality. In cases where authors did not include sufficient details, additional web searches were conducted using keywords from the article or lab name. Through this process, many articles referenced the same RLs, which helped narrow down the list to only 25 articles for detailed evaluation.

During this evaluation, specific criteria were used to filter the RLs including: type of access (paid, free, trial), language, lab status (active/inactive), HDL support, experimental time available for each user, and FPGA board compatibility. As a result, only four (4) RLs were identified as potential options. Table 2 presents a comparison of these options.

Common features of all options included web-based interaction and camera-based results capture (except for E2LP). Users could see the results of their designs and the response of the remote equipment in real time. Access was generally free, with LabsLand offering a trial option with limited functionality or access time, after which full access required payment. Interaction with the tool was in English in all cases and in Spanish for LabsLand. These four RLs were active and covered basic digital electronics topics.

Table 3 shows the final criteria considered for the selection of the remote laboratory. These criteria are explained in detail below.

- Technology: the lab's technology is essential to ensure service stability and compatibility. Web-accessible tools were prioritized to eliminate the need for local program installations. Three of the four options evaluated provided updated environments, and none required incompatible plug-ins. The E2LP RL, although active, had an outdated and less usable interface.

Table 2 Comparison of potential remote labs suitable for this study

Reference	Name	Access	Language	Status	Main Topic
Morgan et al. (2018)	Vicilogic 2.0	Free	English	Active	Combinational and sequential logic, RISC-V essentials
Kłoda & Piwiński (2017)	E2LP RL	Free	English	Active	Combinational logic
Schwandt & Winzker (2019)	FPGA Vision Remote Lab	Free	English	Active	Combinational logic basics, image processing
Orduna et al. (2016) and Angulo et al. (2019)	LabsLand FPGA laboratory	Paid, Trial	English, Spanish	Active	Combinational and sequential logic

Table 3 Final criteria for the selection of the remote laboratory

Lab name	Technology	Experiment visualization	Reservation management	Authentication	Activity logs	Topics and FPGA Support
Vicilogic	Web-based	√	√	√	x	√
E2LP RL	Web-based & locally installed	x	√	√	x	√
FPGA Vision Remote Lab	Web-based & locally installed	√	√	√	x	√
LabsLand FPGA Laboratory	Web-based	√	√	√	√	√

- Experiment visualization: this feature was considered key. Three out of the four options included camera-based features, while E2LP RL offered a virtual interface.
- Reservation management: booking of resources was critical for timely access to practices. All options demonstrated adequate features for this criterion, including administrative support.
- Authentication: all tools allowed free access to practices, subject to registration and proper use of resources.
- Activity logs: only LabsLand offered usage statistics, which were critical for collecting data on students' interactions with the tool and evaluating their experience. This included analysis of peak usage hours and days. LabsLand also facilitated the integration of student groups enrolled in LMS platforms such as Blackboard or Moodle (Buitrago et al., 2018).
- Topics and FPGA Support: the functionality of the tool to cover fundamental topics in digital electronics, with an emphasis on HDL practice, was evaluated. The selected tool had to support FPGA hardware programming and debugging. All options allowed interaction with an FPGA, but only LabsLand offered an editor with a dedicated HDL coding interface that covered all stages of the workflow mentioned by Mohsen et al. (2019).

Ultimately, the remote lab offered by LabsLand was chosen as the most suitable option. In combination with the traditional lab (TL), it formed the basis of the hybrid laboratory for this study.

LabsLand

LabsLand is an initiative that aims to expand experimentation opportunities for educational institutions or students. Specifically, its remote laboratory offers fundamental digital electronics topics and an interface for coding HDL designs, as shown in Figure 1. In addition, it provides tools for multiple file management, syntax highlighting, and debugging.

Once the code is debugged, students can implement their designs on a remote FPGA device, with the results visualized via a live camera feed. Figure 2 shows an example of this feature. More detailed information about LabsLand is available on their website (https://labsland.com/). LabsLand has received positive feedback from students in previous experiences, as highlighted by Mayoz et al. (2020), indicating that students found it a helpful complement to their learning in digital electronics.

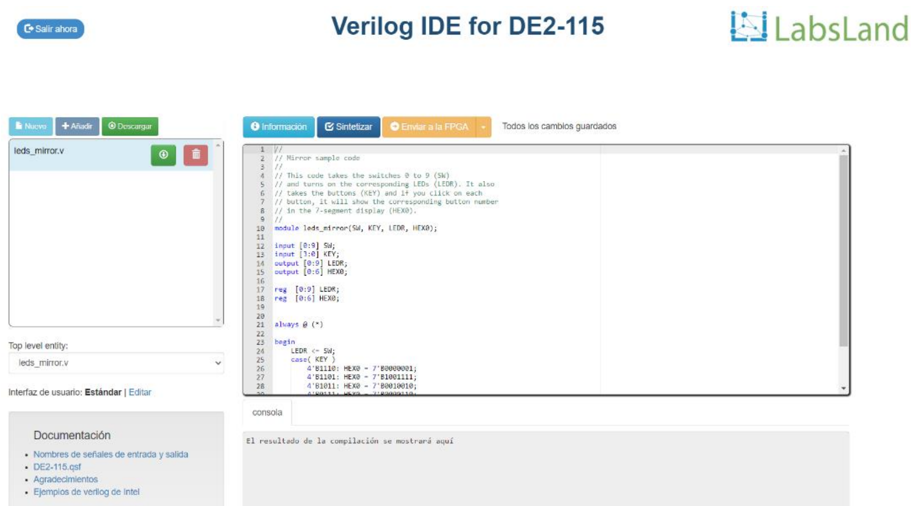


Fig. 1 Screenshot of the graphic user interface of LabsLand showing the HDL development environment

Fig. 2 Interaction with the FPGA board in real time and via video streaming in Labsland

Hybrid laboratory (HL): Integration of traditional lab and remote modalities

The HL combined traditional labs (TL) with remote labs (RL). Following a flipped approach (Velosa, 2020), students alternated between on-site traditional practices and remote activities. For on-site labs, students worked in groups under the supervision of a professor, using university facilities. Meanwhile, remote practices were conducted via Labsland, allowing students to interact with FPGA devices from their personal computers or mobile devices. Table 4 outlines the distribution of labs, topics covered, and the modalities used.

Table 4 Distribution of the six laboratory practices across hybrid laboratory modalities and their associated topics

# Lab Assignment	Topic of assignment	Modality
-	Introduction 1	TL
-	Introduction 2	RL
1	Combinational Logic	TL
2	Combinational Logic	RL
3	Sequential Logic	TL
4	Sequential Logic	RL
5	Finite State Machine	TL
6	Finite State Machine	RL

Importantly, the topics covered in the hybrid laboratory were consistent with the traditional course curriculum. During the introductory sessions, students were informed about the lab topics, the procedures, and how the activities would be conducted. They were also asked to form work groups of up to three members. In addition, they were briefed on academic assessments and invited to voluntarily participate in the research by signing an informed consent form. As for the lab assignments (1 to 6), each followed a three-step structure: pre-report, physical implementation of circuits, and report. In the pre-report, students conducted theoretical analyses and designed circuits. Then, during the implementation phase, they tested circuit functionality and measured physical variables (on-site or remotely). Finally, in the report, they documented and discussed the main results.

Study design

A convergent mixed-methods quasi-experimental study was conducted to analyze the effects of an educational intervention using the hybrid laboratory (independent variable) on students' motivation to learn (dependent variable) and their academic performance (dependent variable) in a course covering basic concepts of digital electronics circuit analysis and design. This research design included two groups of student participants: an experimental group and a control group. Students in the experimental group used the hybrid laboratory scheme for their course practice, alternating between hands-on and remote modalities. Students in the control group used only the hands-on laboratory scheme for their practice. The data collected to characterize the dependent variables included both quantitative and qualitative types, with no priority given to one type of data in addressing the research question.

Participants

The study involved 34 students enrolled in a digital electronics course, with 17 students in the experimental group and 17 in the control group. Participants were selected using a convenience sampling method (non-probabilistic), as there were no restrictions or controls

Table 5 Characteristics of the participants in the study

Group	Number of students	Ages (years)	Gender (%)
Experimental	17	19 to 25	Male: 82% Female: 18%
Control	17	19 to 22	Male: 76% Female: 24%

on group formation. The use of convenience sampling allowed for several practical advantages, including ease of access to participants and a reduction in time and cost. However, it is important to acknowledge the limitations of this method in terms of its ability to be generalized. The experimental and control groups completed the six exercises listed in Table 4. The students were from the electrical engineering, electronics engineering, and mechatronics engineering programs at National University of Colombia, Bogotá campus. The characteristics of the participants are detailed in Table 5.

Educational intervention

The educational intervention was developed in the five stages shown in Figure 3.

1. Presentation of the laboratory components: The first phase consisted of conducting the introductory sessions listed in Table 4.
2. Pre-test administration of the MSLQ-Colombia: In the second phase, students completed the MSLQ-Colombia questionnaire for the first time. This questionnaire characterizes learning motivation and is described in detail in the following section. Both the experimental and control groups participated in these first two phases.
3. Demonstration of the practice elements: The third phase introduced the HO and RL modalities to the experimental group. Introductory exercises in both modalities were conducted to help students become familiar with the tools available. Meanwhile, the control group received information about the HO modality as usual, with no changes.

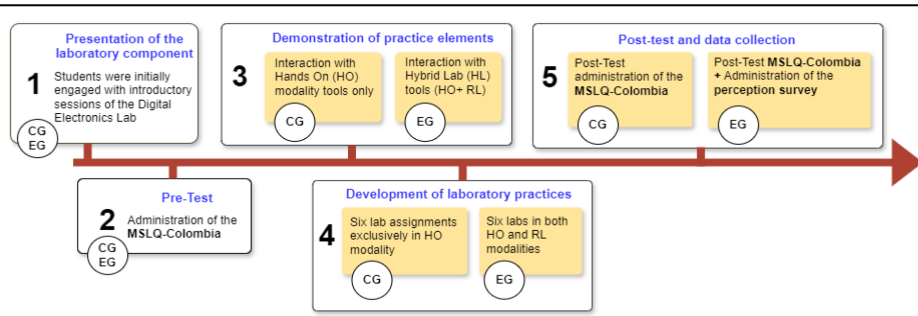


Fig. 3 Methodology of educational intervention (GC: Control group, GE: Experimental group)

4. Development of laboratory practices: In the fourth phase, students in both groups performed six (6) practices. The experimental group alternated between the HO and RL modalities, while the control group used only the HO modality. At the end of this phase, lab report grades were collected to assess the impact of this educational experience on academic performance.
5. Post-test application and data collection: The fifth stage involved the final data collection. The MSLQ-Colombia was administered again to both groups, and the experimental group was asked to complete a perception survey about their learning experience with the HL. All test scores and other data were collected and organized for analysis.

Data collection instruments and data analysis techniques

Three instruments were used for data collection: MSLQ-Colombia, a perception survey, and the laboratory grade report.

The MSLQ-Colombia (Motivated Strategies for Learning Questionnaire-Colombia) is a self-report questionnaire designed to characterize students' motivation for learning and their use of learning strategies (Ramírez-Echeverry et al., 2016). The MSLQ-Colombia is an adaptation from the MSLQ (Pintrich & De Groot, 1990). The MSLQ is widely recognized and frequently used in educational research on self-regulated learning processes (Schunk, 2005). The MSLQ-Colombia was validated for construct validity and internal consistency reliability among engineering students in Colombia. The subscales exhibited robust reliability, with Cronbach's alpha coefficients as follows: intrinsic goals (0.70), extrinsic goals (0.76), task value (0.92), control of learning beliefs (0.79), self-efficacy for achievement (0.81), self-efficacy for learning (0.60), and anxiety (0.75) (Ramírez-Echeverry et al., 2016). Both the experimental and control groups completed the items related to learning motivation before and after the intervention. Each item was rated on a Likert scale from 1 to 7, with options indicating the degree of agreement/disagreement between the student's perception and the meaning of the item, resulting in quantitative data.

Data from the MSLQ-Colombia were first analyzed using descriptive statistics to provide insights into the various motivational aspects. Then, the impact of the HL implementation on the motivational aspects was evaluated using the Wilcoxon statistical test. This test was chosen due to the sample size and the non-normal distribution of the data. The null hypothesis (H0) was that the HL modality had no effect on students' motivation to learn HDL in the Digital Electronics course, while the alternative hypothesis (H1) was that the hybrid laboratory modality had an effect. A significance level of 0.05 was selected. Thus, a p-value less than this value was considered significant, suggesting that the hybrid laboratory had a significant effect on motivation (Bryman, 2012).

The perception survey included questions about specific aspects of learning motivation and the perceived learning experience of the experimental group using the HL. The survey corresponded to the seven motivational aspects described in the MSLQ-Colombia and included 14 questions (7 yes/no and 7 open-ended). Additionally, 2 questions addressed the overall impact of the hybrid lab on motivation and academic performance, while 1 multiple-choice question assessed students' preferences for elements of the hybrid lab. The survey provided both quantitative and qualitative data.

Open-ended responses were analyzed using thematic analysis (Bryman, 2012). First, initial exploration of responses provided general content ideas that guided subsequent analyses. Then, open coding identified central themes, which were then grouped into categories. Through iterative reviews, relationships between themes were identified via axial coding, providing a rich understanding of student perceptions. Each response could reference multiple categories and themes, providing rich information relevant to both research interests and emerging themes. Interpretations were made to address the research question, with initial analysis by the principal investigator and subsequent review by two experts for increased objectivity.

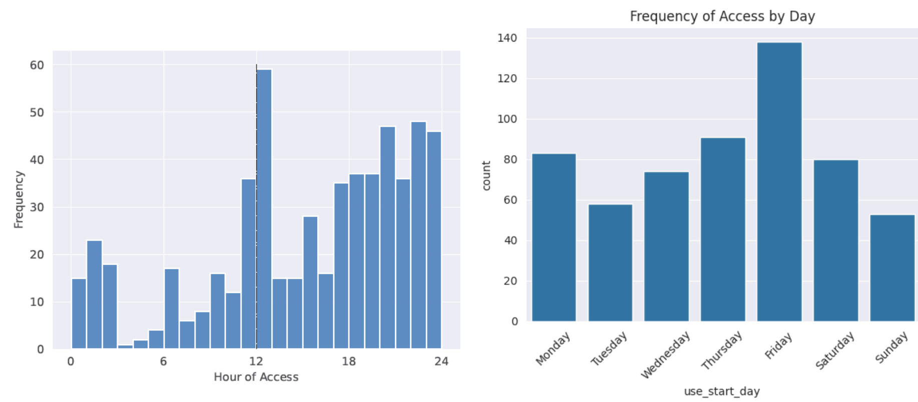
Finally, grades from students' laboratory reports provided quantitative data on academic performance. Students submitted six reports, one for each lab. Each grade assessed aspects related to the student's work, including Verilog scripts, with descriptive statistics used to analyze trends in performance over time for both the experimental and control groups. The grading of the Verilog scripts was not blind to the lab mode, as it was easily identifiable whether the code was developed in the traditional lab (TL) or via the remote lab (RL). However, it is important to note that the evaluation criteria for the Verilog scripts submitted by the students were the same for both laboratory modes. In both cases, the evaluation focused on whether the code contained errors related to good coding practices.

Results

Use of the remote laboratory

The educational intervention allowed students in the experimental group to complete and supplement their course practice using the Labsland remote laboratory. The Labsland platform records students' activities, providing detailed insights into their interaction with the remote lab.

Figure 4 presents data on students' access patterns to the remote laboratory during the intervention period. Figure 4(a) shows the average number of accesses per hour, highlighting the times when students were most active in conducting experiments and tests. Figure 4(b) shows the average number of accesses per day, providing a daily overview of usage throughout the intervention.



(a) (b)

Fig. 4 Average access times for the remote lab (RL): (a) Average hourly access, (b) Average daily access

The data shows that students frequently accessed the remote lab daily to perform tests and experiments, indicating their active engagement in the practical work necessary for learning to design digital circuits using HDL. The highest access times were concentrated after 6 pm, with a notable peak around noon. In addition, students conducted experiments and tests in the RL every day of the week, including weekends, with the highest activity observed on Fridays and Thursdays. Additional platform logs confirm that all students in the experimental group accessed the remote lab at least once during the intervention period.

Motivation in learning

The results of the MSLQ-Colombia questionnaire administered to both the control and experimental groups at the beginning and end of the educational intervention (pre-test and post-test) are presented in Table 6. This table presents the mean responses for each motivational aspect, both in the pre-test and post-test phases, along with their differences and associated standard deviations. The last column shows the p-value from the Wilcoxon test, which indicates whether there was a statistically significant difference between the pre-test and post-test scores within each group.

Overall, the averages for each motivational aspect were above 4.2 (on a scale of 1 to 7) in both the pre-test and post-test phases. Given that the neutral or average score is 4, it can be concluded that students in both the control and experimental groups had a medium to high level of motivation in various aspects. Therefore, it is evident that students enter and maintain a medium-high level of motivation for this course. However, it is worth noting that the aspect of anxiety also showed high levels. This result indicates a situation that requires further study and intervention to reduce these anxiety levels. In addition, the

Table 6 Pre-test and post-test scores of the MSLQ-Colombia applied to the control and experimental groups

Motivational aspect	Group	Pre-Test average	Post-Test average	Difference	Pre-Test standard deviation	Post-Test standard deviation	Wilcoxon p-value
Task value	Control	5.85	5.50	-0.35	1.15	1.35	***0.0224**
	Experimental	5.89	5.50	-0.39	1.18	1.08	***0.0222**
Intrinsic goal orientation	Control	4.88	4.75	-0.14	1.07	1.18	0.5281
	Experimental	4.65	4.82	0.18	1.13	1.66	0.6085
Extrinsic goal orientation	Control	4.60	4.24	-0.37	1.53	1.75	0.2342
	Experimental	4.84	4.47	-0.37	1.52	1.75	0.2770
Self-efficacy learning expectations	Control	5.40	5.07	-0.32	1.32	1.51	0.1857
	Experimental	5.46	5.25	-0.21	1.30	1.27	0.2966
Self-efficacy performance expectations	Control	5.68	5.03	-0.65	1.06	1.33	***0.0023**
	Experimental	5.79	5.51	-0.28	1.07	1.07	0.1418
Learning control beliefs	Control	5.76	6.19	0.43	1.37	0.90	***0.0374**
	Experimental	5.62	5.53	-0.09	0.88	1.10	0.6773
Anxiety	Control	5.40	5.24	-0.16	1.74	1.73	0.4567
	Experimental	4.48	4.33	-0.15	1.94	2.05	0.5902

* p-value < 0.05 (statistically significant difference)

standard deviation for this specific aspect was also high, indicating that the high levels of anxiety were not uniform among the students participating in this educational experience.

When analyzing the difference between the post-test and pre-test means for each motivational aspect using the Wilcoxon test, several statistically significant results were observed:

- In the control group, task value and self-efficacy performance expectations showed negative differences, while learning control beliefs showed a positive difference. Specifically, students in this group slightly decreased their ratings of the importance of laboratory activities (from 5.85 to 5.50) and their expectations of self-efficacy to obtain good grades (from 5.68 to 5.03). Conversely, they improved their perception of controlling their learning process (from 5.76 to 6.19).
- In the experimental group, a statistically significant difference was observed only for task value, which decreased from 5.89 to 5.50. Interestingly, students in the control group also reported a significant decrease in this motivational aspect.

Finally, the quantitative results showed no significant changes in the remaining motivational aspects.

Students' opinions survey

Two main themes emerged from the thematic analysis of the open-ended responses in the student survey: Motivation to learn, and emergent benefits of the HL.

Theme: Motivation to learn

Table 7 presents the resulting categories related to motivation to learn, the percentage of mentions for each category relative to the total number of student perceptions (opinions),

Table 7 Resulting categories related to the theme: Motivation to learn

Category	% mentions	Description	Example of opinions (translated from Spanish)
Self-efficacy expectations in performance	21.3%	Opinions related to students' judgments about their ability to achieve good grades by interacting with the remote lab (tool).	*"Yes, better performance can be achieved. With the possibility to experiment remotely, the time available for the course increases."*
Beliefs about learning control	20.2%	Opinions indicating that the tools available in this educational experience helped to improve their autonomy and thus control over their learning. In addition, they were encouraged to seek out information on their own to improve their understanding of Verilog.	*"...being able to implement the code almost anytime motivates you to spend more time developing and working independently to get the code right."*
Task Value	18.0%	Refers to opinions about the increased interest and importance of learning the lab topics due to the use of different tools available in this educational experience. This includes those who speak of an improved perception of the course.	*"The hybrid lab allowed me to better see the practicality of the course and increased my desire to learn it."*
Anxiety	18.0%	Opinions related to increased confidence in presenting academic activities for assessment purposes, such as lab reports. This includes increased confidence in preparing for practical assignments.	*"Having more time to explore the language and coding errors, there is more mastery of the subject at the time of evaluation."*
Extrinsic goal orientation	7.9%	Opinions about the goals driving the learning of the topics covered in the practical component of the course. In general, it was found that the tools available in this academic experience did not influence students to change their initial goal orientation.	*"I don't think it influenced much, I always wanted to get good grades."*
Self-efficacy expectations in learning	7.9%	Opinions of students who perceived that the tools available in this educational experience helped improve their confidence in being able to learn and understand the activities of the lab.	*"Because of the number of tests and experiments I was able to do, I became confident that I could achieve optimal results."*
Intrinsic goal orientation	6.7%	Opinions that showed the effect of the tools available in this educational experience on their curiosity, desire, and willingness to explore the topics covered in the labs.	*"...the hybrid lab gave me more ease in using the software, which motivated me to try new and different things in the labs."*

a description of their meanings, and examples of student opinions. In total, 89 perceptions of the students in the experimental group were linked to the categories under this theme.

The qualitative data analysis revealed that some students perceived improvements in their motivation to learn thanks to the use of the hybrid laboratory, in contrast to the quantitative results obtained with the MSLQ-Colombia. The categories of self-efficacy expectations in performance and beliefs about learning control emerged as the most commented on motivational aspects by the students. They indicated that the ability to practice at any time through the remote laboratory improved their expectations of obtaining better results and gave them a greater degree of control over their learning process of the laboratory topics. In addition, task value was the third most commented on motivational aspect. Students perceived that the activities performed in the laboratory allowed them to better understand the applicability of the topics of the course. This result differs from the quantitative data on the same motivational aspect, which showed a statistically significant decrease in the data collected with the MSLQ-Colombia. Finally, the opinions related to the improved confidence in presenting academic evaluation activities due to the interaction with the tools available in this educational intervention also highlighted.

Theme: Emerging benefits of the hybrid laboratory

In addition to the motivational findings, the thematic analysis provided insights into the emergent benefits of the hybrid laboratory on learning HDL. Table 8 presents several categories related to the broader effects of this educational experience. A total of 164 perceptions of the students were grouped under this theme.

It is worth noting that these emerging benefits were supported by numerous student opinions, even exceeding the mentions related to motivation and academic performance.

Table 8 Resulting categories related to the theme: Emerging benefits of the hybrid laboratory

Category	% mentions	Description	*Example of opinions (translated from Spanish)*
Personal management of learning	27.4%	Opinions mentioning the benefits for managing effort in the learning process. Time management, the ability to experiment more and do more testing are part of this category.	*"With the hybrid lab, more time can be devoted to practice, and therefore better results can be expected."*
Ease of access to resources	23.2%	Opinions discussing the ease of access to the remote lab and the possibility of frequent practice. Students appreciated the ability to access the lab from any device (PC or mobile phone) and to practice at any time.	*"Yes, it greatly increases the ease of work, comfort, and the ability to work with different devices such as cell phones."* *"Yes, because it allows students to practice at any time, not only during traditional hours."*
Understanding and mastery of the course content	13.1%	Perceptions of benefits for learning Verilog coding, understanding course concepts, and developing practical lab skills.	*"It helps to better understand the course concepts."* *"It helped me better understand the Verilog language."*
Preparation and execution of lab assignments	10.4%	Opinions on the benefits of the hybrid lab tools for the lab activities. They mention the usefulness and advantage of the remote lab for pre-report preparation and general lab development.	*"With the remote lab, you could get an idea of the practice, and with the designs, it allowed you to answer questions and do more effective preparation."*
Consideration of available tools	6.7%	Groups of opinions that recognized and positively evaluated the tools available in the hybrid lab as a useful addition to learning.	*"Yes, it was an extra tool that helped a lot in facilitating the challenges of the course."*
Improved confidence and safety to experiment with the FPGA due to practical experience	6.7%	Opinions on the benefit of the remote lab before hands-on work. Practicing with the remote lab gave students confidence and safety before interacting with FPGA boards by reducing their fear of damaging a physical component.	*"Not worrying about damaging the FPGA helps a lot."* *"Being able to experiment more gives more confidence because mistakes have already been made."*

Specifically, students frequently highlighted the hybrid lab's benefits for time management, ease of access, frequent practice, improved understanding of lab topics, and confidence in using equipment.

Preferences for laboratory features

The final question of the perception survey asked students in the experimental group to identify the features they considered important in both the remote and hands-on laboratory modalities. Figure 5(a) shows the results for the remote lab, and Figure 5(b) presents the results for the hands-on lab.

Based on students' responses, there was a notable preference for the remote laboratory, with the most favored features being ease of access (via the Internet, at any time, with no software installation) and ease of interaction with the remote FPGA. It is important to note that students' preferences for the remote laboratory might have been influenced by their experience with remote education during the COVID-19 pandemic (Ricardo et al., 2023; Almeida et al., 2022). The flexibility and accessibility they became accustomed to during that time may explain why features like ease of access and Internet-based interaction were highly valued. In contrast, students emphasized the ability to interact with the physical FPGA board in the hands-on lab.

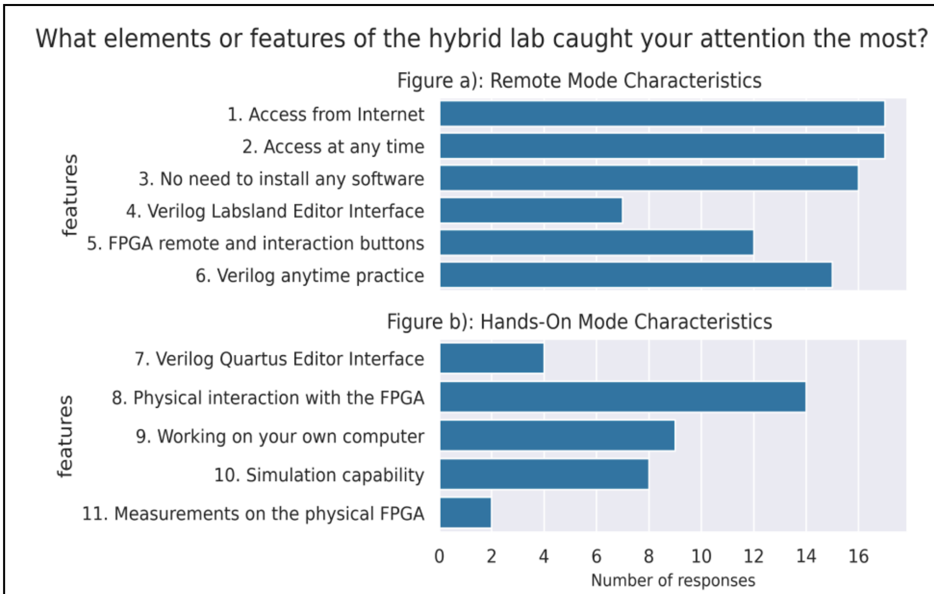


Fig. 5 Preferred features of the hybrid laboratory, according to students in the experimental group

Academic performance

Academic performance results were determined from the grades of students' laboratory reports, which were graded on a scale of 0.0 to 5.0. Figure 6 illustrates the progression of grades for both the control and experimental groups over six reports, showing the group average grades for each report.

In addition, Figure 7 shows the evaluation results for the Verilog scripts attached to each report, showing the group averages for each script.

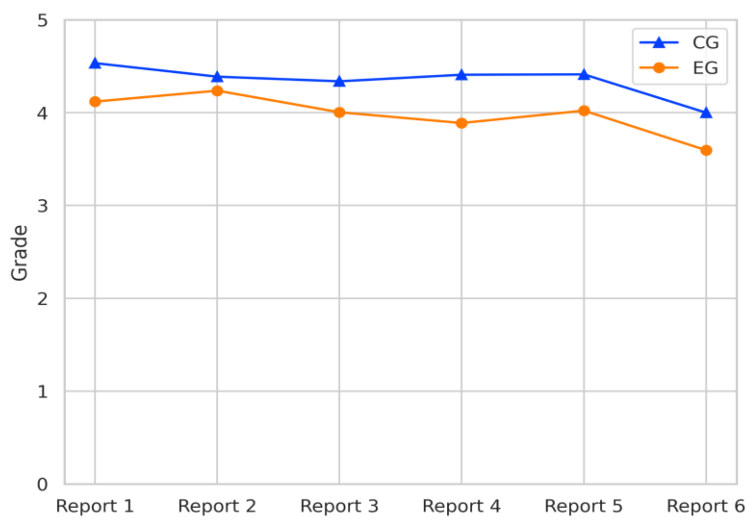


Fig. 6 Grades on laboratory reports submitted by the students (CG: Control Group; EG: Experimental Group)

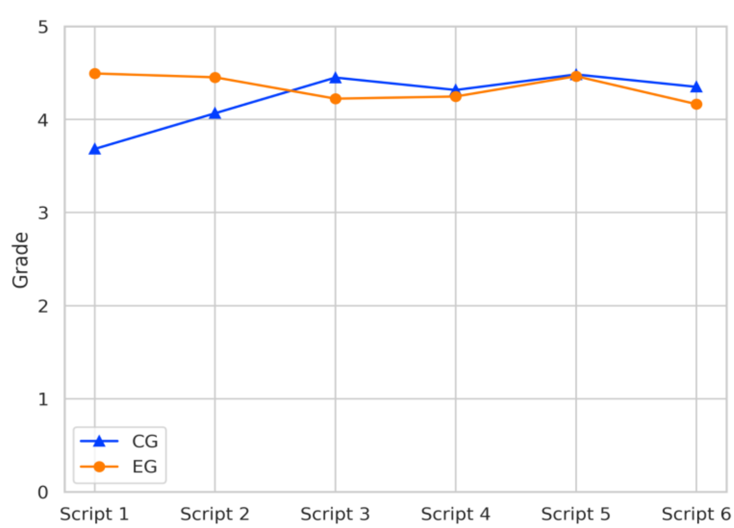


Fig. 7 Grades on laboratory Verilog scripts attached to reports submitted by students

The performance graphs show a slight downward trend in grades for the laboratory reports, a common observation for both groups. For the scripts, the trend is less clear, with grades around or above 4.0. The grading process for these activities was identical for both groups and was performed by one of the researchers involved in this study. According to the Mann-Whitney U test, the grades for the laboratory reports were significantly different between the groups, but no significant difference was observed for the Verilog script grades.

Discussion

This study designed an educational intervention to establish a hybrid laboratory (HL) combining two modalities: traditional (TL) and remote (RL). The results allowed us to address the research question: what are the effects of a hybrid laboratory on students' motivation to learn an HDL and their academic performance in a course on the fundamentals of digital electronics?

Regarding motivation to learn, students showed a medium-high level of motivation at the beginning and at the end of the course. This result was common to both the control and experimental groups, indicating that students generally maintained their level of motivation throughout the course. The quantitative results for the experimental group indicated that the hybrid laboratory did not have a significant impact on any of the motivational aspects.

Furthermore, quantitative data collected at the beginning and end of the course revealed a decrease in task value for both groups of students. This finding suggests that the hybrid laboratory was not the cause of this decrease; rather, a common factor may have affected both groups, reducing the perceived value or relevance of the laboratory activities. The qualitative data, however, presents a conflicting picture for the experimental group: 18% of the students' perceptions reported that using the tools in the hybrid laboratory increased their interest in and importance of the lab topics (see task value from Table 6). This discrepancy between the quantitative and qualitative analyses of task value could not be resolved with the current data but raises an interesting line of investigation to explore the causes of this contradiction and the observed quantitative decrease.

Moreover, the qualitative approach provided additional insights into other motivational aspects. One of these aspects is self-efficacy performance expectations, which received considerable attention. Students' comments indicated that the tools and experiences contributed positively to their expectations of achieving good grades. However, some students noted that this benefit applied only to the laboratory component, with some explicitly attributing this benefit to the remote laboratory. A few opinions indicated that the experience did not contribute significantly to this motivational aspect. It is also worth noting that students who did not use the hybrid laboratory (control group) were found in the quantitative results to have significantly lower self-efficacy performance expectations. This suggests that while students who used the hybrid laboratory improved their performance expectations (qualitative results), those who worked only with the hands-on lab had decreased expectations (quantitative results). This finding suggests that using the hybrid laboratory may help improve academic performance expectations.

Another finding relates to beliefs about learning control. A considerable number of perceptions of students who used the hybrid laboratory indicated that their motivation in this aspect improved. Specifically, some indicators of this phenomenon relate to autonomy and self-directed inquiry. Students mentioned that this experience fostered their autonomous learning and ability to explore topics independently. Some highlighted the encouragement to learn the Verilog language on their own. Only one comment contradicted these statements. According to Morelli et al. (2023), increased autonomy is a driver for generating a genuine and broad interest in learning (intrinsic goals), which contributes to a positive learning process. Lin et al. (2017) propose a reciprocal relationship between autonomy in learning and intrinsic goal orientation. In this study, we can affirm that the hybrid laboratory primarily activated students' learning control, as evidenced by numerous comments about the autonomy and inquiry that the hybrid laboratory encouraged. There were also comments about the effect on intrinsic goal orientation, although to a lesser extent.

Additionally, qualitative analysis revealed benefits of using the hybrid laboratory in other motivational aspects. Some perceptions pointed to a reduction in anxiety associated with assessment processes, resulting in increased confidence in completing lab assignments. This finding is consistent with Siong and Thow (2017), who emphasize that making mistakes—part of the learning process—can increase motivation. Thus, tools that allow for making mistakes, even intentionally, facilitate the establishment of the experience, reflection, and application process described by Siong and Thow (2017). Although less frequently, improvements in intrinsic and extrinsic goals were also noted. Some students reported increased curiosity and a desire to learn beyond simply achieving high grades.

Soft criteria such as motivation, self-efficacy and beliefs about learning control provide insight into students' attitudes and self-regulated behaviors that play a crucial role in learning. These factors may not translate directly into measurable outcomes such as grades, but over time they influence students' engagement, persistence and confidence in tackling complex tasks.

In terms of academic performance, results were primarily derived from the grades of laboratory reports and Verilog scripts. The data showed a downward trend in report grades from Report 1 to Report 6 for both groups. However, the control group had higher grades than the experimental group. This slight decrease in report grades may be attributed to the increasing complexity of the exercises, a trend also observed by Barak et al. (2016). Moreover, no significant differences were observed in Verilog script grades, but the control group demonstrated an upward trend in grades, while the experimental group's grades remained relatively constant. Previous studies, such as Steger et al. (2020), suggest that students in traditional lab settings may outperform those in virtual labs, though the effect size is small. Conversely, Abdulwahed (2010) and Lei et al. (2018) found that students in hybrid labs demonstrated superior academic performance. In this study, qualitative data indicated that students appreciated the hybrid lab tools for their flexibility and frequent practice, which they believed could positively impact grades. The improvement in autonomy and time management indicated by the experimental group students should be consistently reflected in academic performance. Pérez-Villalobos et al. (2018) argue that more effective organization of academic activities and free time can reduce the negative impact on performance. However, the academic performance of the experimental group in this study did not show a better average than the control group. Thus, further long-term studies with larger sample sizes are needed to better understand these findings.

Finally, thematic analysis of the qualitative data revealed emerging categories that complement and extend the findings of this educational intervention:

- Students reported that the hybrid laboratory tools improved their personal management of learning. They perceived improvements in time management and autonomy, allowing them to work more efficiently on lab assignments. Thus, implementing this initiative alongside other strategies could optimize students' use of time and organization. This addresses a common challenge, as Acevedo et al. (2015) highlighted the lack of good study habits in engineering education.
- Regarding teamwork, Viegas et al. (2018) mentioned that the remote laboratory modality had little impact in their study. However, in this study, some perceptions indicated that the remote laboratory helped to better coordinate teamwork times. Given that all participants in the experimental group used the remote laboratory, this may have contributed to the coordination of teamwork times, although the traditional laboratory modality was crucial for organization and coordination.
- The remote lab was highly valued for its accessibility and flexibility. Students appreciated the ability to practice outside of standard hours, allowing for experimentation at different times and locations. This was reflected in the remote lab usage records, with both day and night access and a preference for weekends. Similar findings have been observed by Winzker et al. (2018) and Monzo et al. (2021), who also highlight the practices that arise from access flexibility. For example, the flexibility of remote labs allows for extended practice time (Buitrago et al., 2018; Viegas et al., 2018). This modality played a fundamental role, offering benefits typical of a non-traditional laboratory, and was highly valued in qualitative outcomes.
- The experience with hybrid laboratory tools improved content comprehension and mastery. Students emphasized the reinforcement in understanding the topic and learning Verilog provided by working with the remote lab. Ayodele et al. (2015)

reported similar findings with the remote modality in learning FSM (finite state machines). In addition, the remote lab experience was positively perceived in preparing and performing lab assignments, which improved fluency and comprehension of the activities.

- The remote lab also helped increase confidence before working with the physical board in the hands-on modality. This is consistent with Viegas et al. (2018), who found that prior remote lab experiences enhanced students' ability to work in hands-on environments. Moreover, the remote lab served as a contingency when physical FPGA boards were unavailable, an option particularly valuable in resource-constrained settings (Moulay et al., 2021). However, it is worth recalling that one of the most valued aspects of the experimental group's hands-on modality was the opportunity to interact with a physical FPGA in the lab. This suggests that while the remote lab has good functionality and remote access, students also appreciated working in the physical lab environment. This finding is consistent with Alsaleh et al. (2022), who mention the importance of maintaining hands-on components in hybrid laboratories to increase and supplement interest in experimentation.
- Finally, the ability to perform multiple tests without risking damage to the FPGA board improved students' confidence and safety, which aligns with Son et al. (2016), who notes that repeating experiments benefits concept understanding. This characteristic is essential for learning, especially for students with no prior knowledge (Almeida et al., 2022).

Conclusions

The purpose of this study was to evaluate the effects of a hybrid laboratory consisting of face-to-face and remote modalities on student learning motivation and academic performance in an introductory digital electronics course. A quasi-experimental design was employed with two groups, control and experimental. Data collection included instruments such as the MSLQ-Colombia, a perception survey, and monitoring of student report grades, providing both quantitative and qualitative data.

Quantitative results revealed statistically significant negative effects on task value for both groups. This common finding suggests that the implementation of the hybrid laboratory was not the cause of this effect, but rather some factor inherent to the course development in the specific context of this study. However, qualitative analysis of the information provided by students in the perception survey identified several benefits of the hybrid laboratory. Participants reported that the experience gave them greater control and autonomy over their learning, which raised their expectations for academic performance. In addition, the flexibility and availability of the hybrid laboratory tools contributed to better personal learning management. Students also expressed a better understanding of course topics and improved preparation and development of laboratory practices. Students' confidence and comfort in handling equipment and experimenting with FPGA devices were also increased.

In summary, the findings of this study demonstrate positive effects of using hybrid laboratories on learning motivation and perceived academic performance, as well as aspects related to the use of learning strategies. These results provide relevant empirical evidence to understand the effects of such learning environments in the context of HDL learning for designing digital electronic devices.

However, the study's limitations, particularly its small and non-randomized sample size, highlight the need for further research. This is of particular importance, given that the statistical power of significance tests such as the Wilcoxon increases with larger sample sizes (Wiedermann & von Eye, 2013). Moreover, parametric tests tend to outperform non-parametric tests like the Wilcoxon when data follow normal or uniform distributions. This further underscores the necessity for more robust samples in future studies. In addition, future research could benefit from a more detailed exploration of socio-demographic factors such as age, gender, educational level, previous experience with digital electronics and socio-economic aspects. These factors may provide valuable insights into how different student profiles respond to hybrid laboratories and how they affect learning motivation and academic performance. Finally, given the considerable student feedback on learning strategies, further research could explore the effects of hybrid laboratories on students' approaches to learning.

Abbreviations

CG: Control Group; EG: Experimental Group; E2LP RL: Embedded Computer Engineering Learning Platform Remote Laboratory; FPGA: Field Programmable Gate Array; FSM: Finite State Machines; HDL: Hardware Description Language; HL: Hybrid Laboratory; HO lab: Hands-On Laboratory; IoT: Internet of Things; LMS: Learning Management System; MSLQ: Motivated Strategies Learning Questionnaire; NTL: Non-Traditional Laboratory; RL: Remote Laboratory; STEM: Science, Technology, Engineering and Mathematics; SRL: Self-Regulated Learning; TL: Traditional Laboratory; VHDL: Very High-Speed Integrated Circuit Hardware Description Language.

Authors' contributions

All authors: Conceptualization, Methodology, Validation and Formal Analysis, Investigation, Writing Original and Draft Preparation, Reviewing and Editing, Data Curation, Supervision and Project Administration.

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Availability of data and materials

The data supporting the authors' findings of this study can be found at the following link: https://github.com/UNPLaS/HybridLab-HDL?tab=readme-ov-file#hybridlab-hdl

Declarations

Competing interests

The authors declare that they have no competing interests.

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