Interaction Design and Architecture(s) Journal - IxD&A, N.63, 2024, pp. 44 - 67
DOI: 10.55612/s-5002-063-003

Promoting Physics Learning and Interest: Evaluating the remote-lab RIALE experience in high school.

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Abstract. A main aspect of scientific education is experimental practice. Online laboratories can be used to replace, support and supplement traditional ones. This study aims to assess the effectiveness of a remote physics laboratory in high school students, utilizing the educational RIALE platform. We hypothesised improvements in learning outcomes, satisfaction, interest in physics, and comprehension of the scientific method. A remote laboratory focused on classical and quantum mechanics was conducted. Researchers carried out four experiments illustrating wave-particle duality using practical setups and interactive demonstrations. Pre- post-test measures, along with satisfaction questionnaires, were administered to a sample of 54 high school students and six teachers.The results did not reveal significant improvements in classical and quantum mechanics knowledge, although variations were observed depending on the topic and school grade. However, the remote laboratory was perceived as a satisfactory experience that stimulated students' interest in physics and the practical application of scientific methods, fostering curiosity and motivation. These findings provide valuable insights for developing educational strategies to more effectively integrate online laboratories into science education.

Keywords: STEM education, remote laboratory, physics, learning, interest, motivation, satisfaction, high school.

1 Introduction

STEM (Science, Technology, Engineering, and Mathematics) education is a broad term encompassing the development of an interdisciplinary curriculum integrating skills from various scientific and technological disciplines [1]. Proficiency in STEM is vital for socioeconomic progress and the advancement of labour and national economies in technology-driven societies [2].

Although STEM education is widely recognised as crucial, the latest OECD PISA 2022 survey [3] has revealed concerning data on students' knowledge and skills in mathematics and science. Between 2018 and 2022, the average performance in mathematics across OECD countries declined significantly by 15 points, marking a record decrease. Reading proficiency also dropped notably by 10 points, while science performance remained relatively unchanged.

The unprecedented declines in mathematics (and reading) highlight the profound impact of COVID-19 on educational outcomes. However, PISA trend analyses suggest that these declines predate the pandemic, revealing a long-term downward trajectory. Additionally, the data indicate persistent disparities: on average, boys outperform girls in mathematics by 9 points, and socioeconomically disadvantaged students are seven times more likely than their advantaged peers to fail to achieve basic proficiency in mathematics.

These challenges call for improved teaching quality and equitable access to STEM education. Such efforts are essential to promote higher levels of knowledge and proficiency in mathematics and science, while also preparing students for autonomous learning.

Technological advancements have introduced new opportunities for enhancing instructional activities, serving as a driving force to support student learning and motivation [4]. Advances in information technology have indeed led to the development of innovative and interactive technological applications that aid in better understanding concepts, phenomena, and scientific theories by students, offering an active learning environment conducive to fostering key skills such as critical thinking and problem-solving abilities [5].

Nonetheless, a substantial body of literature confirms that the impact of technological applications on learning outcomes is generally limited or moderate, with considerable variability in the data. Some promising findings regarding the efficacy of online learning strategies in enhancing students' academic performance in physics have been documented in the literature [6, 7, 8], even when compared to results from traditional learning approaches [9, 10, 11]. Overall, scientific evidence suggests that the influence on learning outcomes is heavily dependent on the quality of teaching rather than the technological applications themselves [12, 13]. Drawing upon findings from various fields of educational research over the past decades, particularly instructional design [14, 15, 16, 17], evidence-based education [18, 19], and cognitive science in education [20], it is possible to outline some fundamental principles for effective teaching [21]. They include: (i) initiating instruction with relevant problems to immediately engage student interest and motivation; (ii) articulating clear learning objectives for both teacher and students, along with the necessary steps to achieve them; (iii) integrating new knowledge with students' existing understanding; (iv) presenting new information gradually and in a structured manner, interspersed with opportunities for practice; (v) fostering ongoing feedback between teacher and student to monitor progress and promote self-awareness and self-regulation; (vi) encouraging reflection on learning processes, including metacognitive strategies; and (vii) employing varied methods for application and retrieval of knowledge over time, such as reinforcement strategies.

Within this framework, the present project was conceived. Developed at CRS4 and built upon their educational platform RIALE (refer to section 3), the project aimed to explore conditions that optimize the advantages of remote laboratories in cognitive learning and student satisfaction. In this context, online experimental procedures were deployed in a physics laboratory focusing on wave-particle duality (refer to section 4.3).

2 Definition of Virtual and Remote Laboratories

Laboratory experimentation is one of the cornerstones of scientific education, a practice that has been integral to the field since the late 1800s [22, 23]. Its theoretical foundation lies in Dewey's theory of social activism [24], which advocates for an active learning model where the child's activity is central. This approach organises knowledge acquisition around problem-solving tasks derived from students' personal inquiries, framed as social work.

Despite its historical significance and the foundational contributions of educators such as Pestalozzi, Dewey, Decroly, Montessori, and Vygotsky, the concept of the school laboratory lacks a universally agreed-upon definition in the literature [22]. In general, laboratories are defined as educational environments where students engage with materials to observe and understand natural phenomena through tools, data collection methods, models, and scientific theories [23].

Through practical experiences, students establish goals, collaborate in groups, perform experiments, and evaluate outcomes. Participation in laboratory activities can significantly enhance students' comprehension of the interplay between empirical research and scientific theories, fostering their involvement in questioning, inquiry design, and the creation and refinement of explanatory models [25].

While the benefits of laboratory experiences are well-documented, several barriers hinder their implementation in schools. These include the significant costs associated with establishing and maintaining laboratories, procuring equipment, and hiring specialised technical staff. Schools must also comply with stringent safety regulations and manage the risks inherent in handling complex equipment and hazardous substances. Additionally, the limited capacity of laboratory spaces restricts the number of students who can participate simultaneously [26]. Another major issue is the outdated state of laboratory facilities in many schools, stemming from inadequate funding for equipment upgrades. This lack of modernisation reduces students' opportunities to engage with advanced experiments that reflect evolving professional demands [27].

Considering the challenges and risks, advancements in digital technologies present promising prospects for laboratory education in schools. Heradio et al. [28] categorize experimentation environments based on two criteria: access to resources (remote or local) and the physical nature of the laboratory (simulated or real). This classification delineates traditional practical laboratories (local access/real resources), single-user virtual laboratories (local access/simulated resources), remote laboratories (remote access/real resources), and multi-user virtual laboratories (remote access/simulated resources), which can accommodate more students simultaneously through a virtual system.

Collectively, virtual and remote laboratories are often referred to as online laboratories (or web-based labs, computer-based labs, etc.). Virtual laboratories provide fully digital environments for simulated experimentation, while remote laboratories enable students to conduct experiments by interacting with physical tools and components via the internet. When combined with traditional laboratories, these setups are often termed hybrid laboratories [29].

According to a second-order systematic review [30] regarding the impact of online laboratories on STEM education for secondary school students, online laboratories can produce learning outcomes comparable to, or even exceeding, those of traditional laboratories. However, their effectiveness depends on factors such as teacher training, alignment of laboratory activities with educational goals, assessment methods, and the integration of online and traditional approaches.

Online laboratories offer significant advantages in terms of accessibility and flexibility. They are accessible 24/7 from any location with an internet connection, allowing students to engage in experiments conducted anywhere in the world without the constraints of physical distance or time zones [31]. This availability encourages autonomous learning and self-directed study. From an economic perspective, online laboratories reduce the need for substantial investments in physical infrastructure, equipment maintenance, and specialised technical staff.

Additionally, resources can be shared across multiple institutions, promoting cost efficiency while maintaining safety standards for students and equipment. Despite these advantages, the effectiveness of online laboratories depends heavily on several factors, including teacher training, the alignment of laboratory activities with pedagogical objectives, and the integration of online and traditional approaches [30].

Virtual laboratories are fully digital environments that simulate real-world laboratory settings, enabling students to interact with virtual representations of tools, components, and processes. These environments are particularly effective as preparatory tools, familiarising students with laboratory practices before they engage in hands-on experiments [32]. Augmented reality and advanced software simulations in virtual laboratories create immersive and interactive experiences, allowing students to explore different scenarios and learn from their mistakes [33].

However, virtual laboratories have limitations. While they support the development of some practical skills, their impact on hands-on capabilities is limited compared to physical laboratory experiences. Furthermore, virtual laboratories often rely on asynchronous interactions, where students communicate with instructors via online platforms such as chat or email, which may lack the immediacy and direct engagement of synchronous interactions [33].

Remote laboratories enable students to conduct real experiments by remotely accessing and controlling physical equipment located in a distant laboratory. These laboratories facilitate direct engagement in inquiry-based processes typical of the scientific method, providing hands-on experiences that help students develop practical laboratory skills [34].

One key advantage of remote laboratories is their ability to combine real-world experimentation with the convenience of remote access. Instructors can provide immediate feedback and monitor student progress during synchronous sessions, ensuring personalised and interactive learning experiences [33]. However, remote laboratories cannot fully replicate the tactile and immersive experiences of traditional laboratories, which remain critical for certain aspects of skill development [35, 36, 37].

Remote laboratories also pose logistical challenges, including the need for robust infrastructure to ensure secure access and scalability. Garcia Zubia [38] highlights several requirements for their implementation, including universality, accessibility from any device without additional software installations, and secure login and password management. Remote laboratories must also provide educational tools for instructors, such as tutorials, detailed explanations, and analytics to monitor learning outcomes. Additionally, pedagogical goals must be clearly defined, encompassing target audiences, key concepts, and intended interaction types [38].

3. The RIALE Experience

3.1 The Remote Laboratory Access System

RIALE, which stands for Remote Intelligent Access to Lab Experiments in Europe, is a didactic approach accessible through a web platform[1]. It has been designed to provide teachers and students with remote access to experimental activities in technical and scientific laboratories across Europe.

The core of the remote laboratory access system integrates with the popular video conferencing platform Zoom. Teachers can book synchronous session time slots on the RIALE platform, which automatically generates a Zoom link to connect the class on the scheduled day and time.

During these synchronous sessions, teachers can control the cameras installed in the partner laboratories. This allows them to select different angles of the ongoing experiment, providing students with a more immersive observational experience. The RIALE IoT system facilitates the camera controls, using the MQTT protocol to enable remote management of the cameras.

Since April 2024 and for interactive practical sessions, RIALE uses a separate solution based on VNC (Virtual Network Computing) technology. This technology allows students to remotely access and control a computer system located in the partner laboratory. From this remote workstation, students can actively participate in the scientific experiment, using specific software and equipment to analyze data and take measurements.

The VNC-based practical sessions complement the synchronous observation sessions, offering hands-on involvement and a deeper understanding of the experimental processes.

3.2 The RIALE Educational Approach

RIALE aims to foster scientific exploration among students and facilitate dialogue between researchers, teachers, and learners. As we pointed out in the previous paragraph, the difficulty for students accessing scientific experimentations [39], particularly for those focused on cutting-edge innovation, increases the distance between real innovative scientific approaches that propose societal solutions and

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[1] The platform has been developed by the Italian research center CRS4 (Center for advanced studies, research, and development in Sardinia) and financed by the Autonomous Region of Sardinia thanks the Development and Cohesion Plan financial framework.

the students' awareness of the evolution of practices and their vital importance in our daily lives.

RIALE aims to assist students to discover and understand high complex scientific experimentations through Europe they could not easily be aware of. Supporting teachers to apply the RIALE approach, we wish to respect the idea that students improve their comprehension of a full scientific experimentation elaborating mental representations. Roy [40] explains the importance of the modelling process to better understand what is really going to happen scientifically (predictive function), and what it could be changed to satisfy new needs (heuristic function). It is a key mental activity to be promoted in parallel with the problem-solving strategy as recommended by Roy [40].

Interactions with experts expose students to real-world research problems, enhancing their understanding of scientific methodologies and fostering connections between academic concepts and practical applications. It aims to motivate students by linking the school curriculum with real-world scientific innovations. Increasingly, science educators are using the same modelling strategy as the researcher to explain the scientific phenomenon under study as reported by Jameau [41, p.13]: "*for Martinand, there is a didactic responsibility in the choice and definition of the empirical referent, because objects and phenomena are not 'given' but are the result of a reading of 'reality'. However, this reading is not necessarily the same for pupils and for educated adults* [42]". The strategy that characterizes the RIALE approach is that of strengthening students' understanding of the objectives that the scientific community sets itself. Research models, whether material or conceptual, are used to represent in significant terms an abstract concept, an idea, an object, an event, or a process [43]. It is at this level of the representation of new scientific knowledge that the synchronous and asynchronous sessions made possible by the RIALE platform may have a role of educational interest. In particular, when the expert himself intervenes in real time to explain the phases of her/his laboratory research, when the student accesses off-line the didactic scientific content that is included in the timeline respecting the chronological phases of the experimentation and when the student access a specific hardware connected to the internet from the real laboratory. The latter strategy allows the student to visualize data obtained during the experimentation and try to interpret data according to what the expert has explained during the synchronous session (metacognitive task).

If the first task of a science teacher is to help students meet the requirements prescribed by educational programs, the description of what and why high innovation is funded and study around the world is not a prerogative of science teaching but still appears a significant learning constructive phase to improve at school. In our situation, the researchers appear as the designers of the problem construction putting in evidence methodology and tools, they need to consider achieving their principal goal [44]. They illustrate (during the synchronous session) the activities required to perform the various steps leading to the collection and analysis of data; steps that the student will retrace off-line through the timeline. The real-life context of the laboratory, the presentation of the expert and the demonstration of his activities can support the study of complex scientific phenomena that arise and take shape in a laboratory. We are talking about the construction of an internal mental model based on the expert's own mental schema, but it is well know how different in terms of complexity these two mental schema are. A complex activity because it lacks conceptual deconstruction: from the expert to the student [45] with the risks of creating conceptual conflicts between very distant dimensions of mental representation. The integration of all the stages of the scientific procedure in a timeline guarantees access to the inductive model proposed by the teacher to convey facts that have already been recorded and are a source of results.

It is not an easy activity to carry out either by the students or by the teachers, especially when it involves a highly scientific content the instructional program does not cover but it may be useful considering a combination of different strategies for learning construction. The research instigator illustrates in his laboratory the activities required to perform the various steps leading to the collection and analysis of data; steps that the student will retrace off-line through the timeline. The real-life context of the laboratory, the presentation of the expert and the demonstration of her/his activities can support the study of complex scientific phenomena that arise and take shape in a laboratory.

The integration of all the phases of the scientific procedure in a timeline guarantees access to the inductive model proposed by the teacher to convey facts that have already been recorded and are a source of results. This setting is defined as the first strategy of the RIALE approach (see Fig.1), which is followed, in addition to the study of the teaching material in the timeline content, by an exercise/comparison phase through direct access to one of the hardware in the laboratory, connected over the internet network. The RIALE approach is defined as the coming together of these three significant moments through which the student is encouraged to learn from the experts' exposition. We often speak of mental modelling from the thinking exhibited by the experts to develop a knowledge representation, to foster understanding of the phenomenon under study, to physically interact with the content (data, images, samples, etc.) and to develop practical skills. Interaction with connected laboratory's hardware is an important opportunity to receive direct feedback.

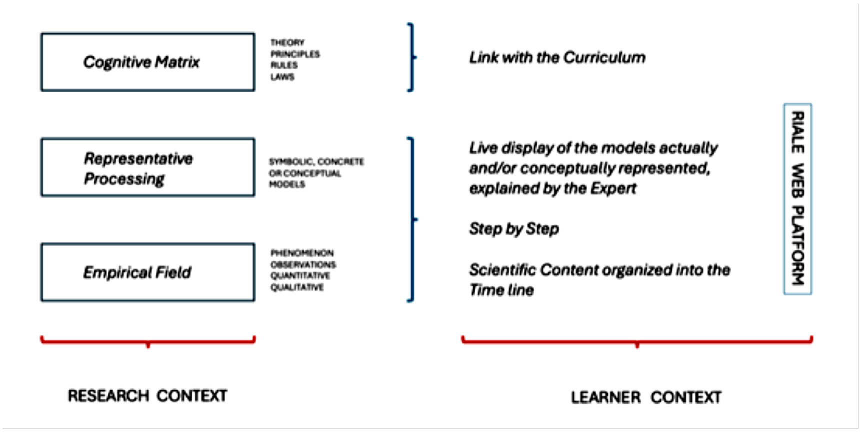

Fig. 1. The RIALE approach.

4. Method

4.1 Context and Participants

A remote laboratory, focused on both classical and quantum mechanics, was implemented in three scientific high schools located in Sardinia, a region that has consistently ranked among the lowest in Italy for scientific and mathematical competencies over several years, while also experiencing some of the highest school dropout rates in the nation. The laboratory was initially introduced to six high school physics teachers (four males and two females) through a series of online meetings. These sessions aimed to familiarise the teachers with the platform's functionality and the laboratory content. The study involved a sample of 108 students (ages 17-19, with 63 in their final year of high school). However, attrition rates were significant, as only 54 students (33 males and 18 females) completed the anonymous questionnaires following the experimental sessions. All participating students provided informed consent for the results of the study to be published.

4.2 Research Questions

The objective of this study was to assess the effectiveness of a remote laboratory in physics. We measured its impact on learning outcomes, satisfaction levels, and interest in the subject among both students and teachers. Specifically, we aimed to address the following questions related to their experiences:

1. Does the utilization of the remote laboratory enhance students' learning outcomes in the topic?
2. What are the levels of satisfaction among students and teachers regarding their experience with the remote laboratory?
3. To what extent does the experience with the remote laboratory contribute to an increase in students' interest in physics and in understanding the scientific method?

4.3 The Remote Physics Laboratory

The remote laboratory, titled "*Waves on the surface of a liquid, Light waves and Electronic diffraction*", was carried out from October 2022 to May 2023 with the collaboration of the Department of Physics of the University of Cagliari. The main topic of the laboratory was the wave-particle duality [46]. It started from waves (mechanical and electromagnetic) and their properties, after that researcher focused on matter and some specific macroscopic properties and phenomenology such as scattering. Four different experiments dealing with the undulatory, and particle properties of matter were shown and discussed.

The first experiment dealt with mechanical waves propagating in a fluid. Researchers showed and discussed diffraction properties of such waves. This introduced the dual behaviour of matter according to experimental conditions to carry the experiment out. The experimental set-up was by Phywe[2].

The second experiment was a flipper-like apparatus, with marbles hitting a screen passing through a slit. This was to explain and show the particle behaviour of matter, that is that massive particles and, in general, macroscopic objects (with a length of the order of centimetres or more) do not diffract. Researchers focused on the phenomenon of elastic scattering and the relationship between the dimension of marbles and the slit.

The third experiment concerned the diffraction of light. A red light emitted by a laser (with a wavelength of about 632.8 nm) passed through some lenses and a slit to be coherently collimated in a beam. The slit can be opened or closed until its size becomes comparable with the laser wavelength. Then, diffraction occurs.

Finally, in the fourth experiment, researchers showed electron diffraction through a suitable experimental set-up by Phywe[3]. In this case, the diffraction manifests with rings on a fluorescent screen. This experiment shows that, under suitable conditions that is an electron passing through a slit (graphite planes) of

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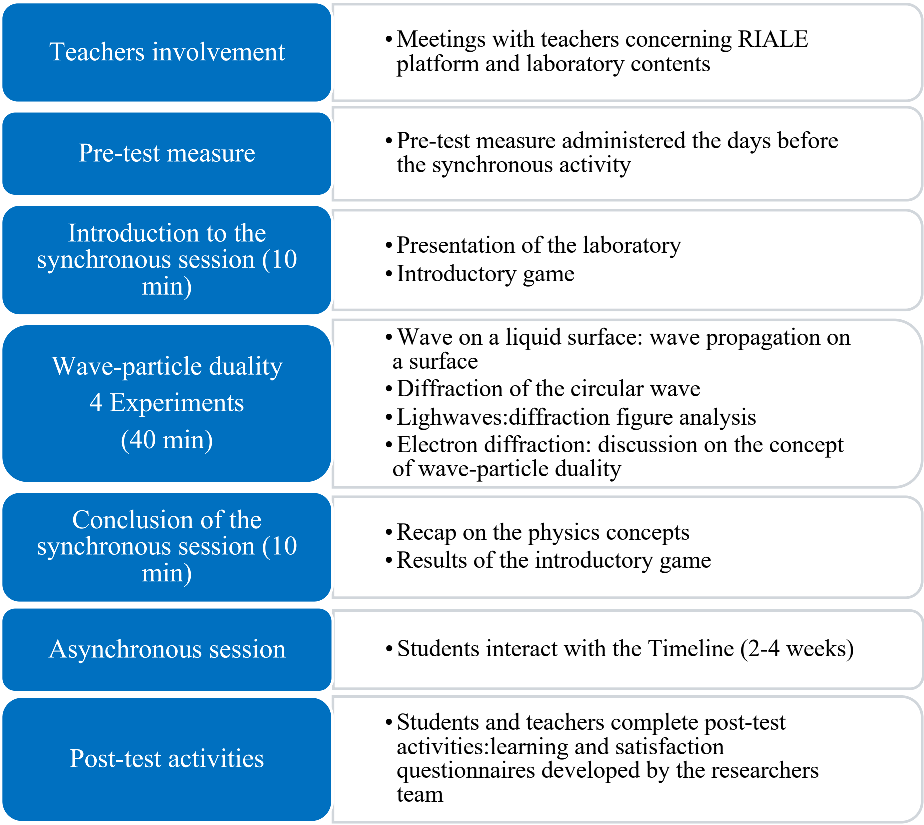
[2] https://www.phywe.com/physics/acoustics/wave-motion/phywe-ripple-tank-with-led-light-source-complete-set_1995/

[3] https://www.phywe.com/experiments-sets/nobel-prize-experiments/electron-diffraction_9532_10463/

dimensions comparable with its wavelength, even what is typically thought as a particle manifests an undulatory phenomenology. Also, to show that in this process the electron does not lose its charge, we used a magnet to move the diffraction figure along the whole screen.



Teachers involvement	• Meetings with teachers concerning RIALE platform and laboratory contents
Pre-test measure	• Pre-test measure administered the days before the synchronous activity
Introduction to the synchronous session (10 min)	• Presentation of the laboratory • Introductory game
Wave-particle duality 4 Experiments (40 min)	• Wave on a liquid surface: wave propagation on a surface • Diffraction of the circular wave • Lighwaves:diffraction figure analysis • Electron diffraction: discussion on the concept of wave-particle duality
Conclusion of the synchronous session (10 min)	• Recap on the physics concepts • Results of the introductory game
Asynchronous session	• Students interact with the Timeline (2-4 weeks)
Post-test activities	• Students and teachers complete post-test activities:learning and satisfaction questionnaires developed by the researchers team

Fig.2. Experimental design

The methodological structure of the laboratory is showed in Figure 2. Firstly, an introductory game was proposed using the “Quizziz” platform to qualitatively measure students’ expectations about phenomena showed during the activity made. Questions had no evaluation intent, rather they just measured their feeling or previous knowledge (especially for students attending the last years in high school) on the subject. This activity lasted ten minutes. After that, the experimental activities started (duration: 40 minutes). The laboratory ended with a general recap on the physics concepts dealt with and the results of the introductory game was discussed in the light of the phenomena observed. The total duration of the activity was about one hour. Contents where targeted: the younger the participants, the less technicalities and details were inserted in the discussion. Despite the online environment, some level of interaction with the class through the mediation of the teacher was guaranteed. Teachers and students attended the online laboratory from their classrooms and a Zoom connection was established, with cameras filming the researchers and the experiments connected to a laptop with a Raspberry system. Each class participated in separate laboratory sessions, resulting in a total of six meetings. In the following two weeks, students are invited to interact with the online tool (Timeline, Fig. 3) for the asynchronous session and to complete post-test activities.

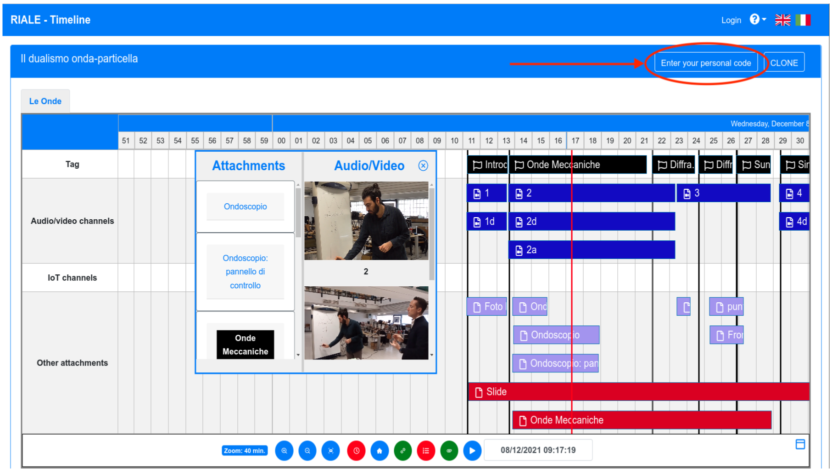


Fig.3. Example of Timeline for the asynchronous session.

4.4 Instruments

The following instruments were administered via a web form:

- A test with six questions related to the specific experimental topics (properties of mechanical and electromagnetic waves, introductory quantum mechanics, diffraction of electrons) developed by the researchers to evaluate students' knowledge before and after the experience. For each question, the students could choose between three answers, only one was correct. The pre-test measure was administered the days before the synchronous activity; the post-test data were collected from two weeks to one month after the synchronous session, to permit the use of the asynchronous online educational interactive tool (Timeline).
- A questionnaire developed by the researchers aimed to measure the students' satisfaction with several dimensions to the remote experience: the usability of

the platform (three items); the topics discussed (three items); the understanding of scientific method (three items); the interaction with researchers (two items). Students could respond using a five-point Likert scale, from 1 (strongly disagree) to 5 (strongly agree). The reliability of the questionnaire is alpha = .778.

- Additional questions regarding students' experience with traditional physics laboratory at school (10 questions; three-point response scale); motivation and interest in physics and in the scientific method (nine questions; five-point response scale); the overall satisfaction with the experience (three questions; five-point scale).
- A teachers questionnaire concerning satisfaction with the experience in terms of interest in topics and students learning (seven items measured on a five-point Likert scale, alpha = .69).
- Additional teachers' questions regarding laboratory practice at school (five questions) and their final considerations on the experience (four questions).

All the data were analysed with the Jamovi software. Paired samples t-tests and McNemar test are used to analyse pre- post-test study design. The McNemar test is a non-parametric test used to compare the frequencies of paired samples when dependent variable is dichotomous with two mutually exclusive categories (i.e. correct, incorrect).

5. Results

5.1 Learning

Results indicated no statistically significant difference in overall learning (t = .823; p = .207; Cohen's d = 0.115). Examining the questions separately, there was a statistically significant difference on the frequency of correct answers before and after the laboratory experience only for question one and three (McNemar's test, p<.05, Table 1).

Table 1. Statistically significant difference on learning before and after the experience.

	Question – correct answer	χ^2	*p*
LQ1	A mechanical wave is - a perturbation that propagates through a medium	5.33	.02
LQ2	Mechanical waves - carry energy	2.88	.09
LQ3	Diffraction is - a phenomena associated to waves propagation	4.26	.04
LQ4	Light (electromagnetic) waves – carry energy	0.60	.44

LQ5	Electrons are – particles or waves according to how you measure them	0.29	.59
LQ6	When an electron passes through a small slit of a suitable size hitting a screen, you can observe - a diffraction pattern	0.05	.83

Table 2 illustrates the changes in correct responses between pre- and post-test assessments, highlighting improvements in specific areas. For the second and third questions, there is an improvement in the number of correct answers between pre- and post-test; while for the first question (the easiest at the pre-test), there was a clear decrease in the percentage of correct answers.

Table 2. Frequencies and percentages of correct answers.

	Pre-test		Post-test	
	N	%	N	%
LQ1	45	88	37	73
LQ2	28	55	35	69
LQ3	28	55	37	73
LQ4	39	76	36	71
LQ5	38	75	40	78
LQ6	31	61	32	63

Table 3. Frequencies of correct answers by school year.

		Fourth year N = 17		Fifth year N = 34	
	Topic	Pre-test	Post-test	Pre-test	Post-test
LQ1	Mechanical waves	17	17	28	20
LQ2	Mechanical waves	10	14	18	21
LQ3	Electromagnetic waves	8	12	20	25
LQ4	Electromagnetic waves	13	10	26	26
LQ5	Introduction to quantum mechanics	12	16	26	24
LQ6	Electron diffraction	7	9	24	23

When analysing results by school year (Table 3), fourth-year students showed consistent performance across tests, while fifth-year students exhibited notable declines in certain areas.

5.2 Students' Satisfaction and Interest

Results showed high levels of satisfaction for almost all aspects considered, such as: the usability of the platform (SS1, SS4, SS5); the topics discussed (SS6, SS7, SS11); the understanding of scientific method (SS8, SS9, SS10); the interaction with researchers (SS2, SS3; see Table 4). In particular, the item with the highest level of agreement concerned the interest in laboratory topics (SS6), while the items with the lowest level of agreement is related to students' experience with the laboratory, with reference to SS1 concerning the feeling of being immersed in a real experience and SS5 concerning the platform usability.

Table 4. Means and standard deviation of the student satisfaction questionnaire.

Item	Mean	sd
SS1. When I watch the remote experiment and control the camera, I feel in a real laboratory	2.89	.925
SS2. Interactions with the researcher are helpful	3.91	.622
SS3. Watching the researcher's activities remotely helps me understand the scientific experiment I observe	3.80	.683
SS4. The use of Timeline helps me understand the scientific experiment	3.46	.862
SS5. The platform is simple enough that I don't need help to use it	2.81	1.23
SS6. The remote lab topics were interesting	4.15	.563
SS7. The remote laboratory stimulated me further questions about the subject	3.54	.884
SS8. The experience with the remote laboratory allowed me to understand the importance of collecting, analysing and interpreting data	3.74	.650
SS9. The experience with the remote laboratory allowed me to understand how a scientific investigation is conducted	3.70	.717
SS10. The remote laboratory allowed me to reflect and explain the observed phenomena	3.83	.637
SS11. With the remote laboratory I was able to concretely explore phenomena studied at school	3.91	.734

Concerning additional questions related to the traditional laboratory practice at school (see Table 5), it should be noted that less than 15% of students affirm to regularly enter in a physics laboratory at school and that over 35% affirm that physics is often taught through formulas and theories.

Table 5. Percentage of laboratory practice at school.

	Never	Sometimes	Often
1. I entered in a physics laboratory at school	9.3	75.9	14.8
2. I took physics lessons in the laboratory	18.5	66.7	14.8
3. I learned physics at school through the laboratory	24.1	72.2	3.7
4. I took physics laboratory lessons in class	13.0	72.2	14.8
5. Physics at school is taught through experiments	20.4	72.2	7.4
6. Have I ever seen physics according to this scheme: expectations on a phenomenon, observation of a phenomenon, comparison between expectations and observation, theoretical explanation of the phenomenon, collective discussion on the phenomenon and its explanation	29.6	51.9	18.5
7. I have never explained physics through the implementation of an experiment (even during an oral test)	33.3	40.7	25.9
8. Physics in the classroom is taught only with formulas and theory	40.7	24.1	35.2
9. I have attended an online workshop in the past	40.7	57.4	1.9

Percentages of motivation and interest in physics and in the scientific method are showed in Table 6. It should be noted that laboratory experience supports a weak increment to interest and curiosity towards physics and the scientific method (Q5, Q6, Q7, Q8).

Table 6. Percentage of the motivation and interest in physics.

	Not at all	Slightly	Moderately	Very	Extremely
1. I already knew the topics of the online physics laboratory	9.3	20.4	44.4	22.2	3.7
2. I had already debated the topics of the online physics laboratory in class	7.4	11.1	35.2	42.6	3.7
3. I like physics	1.9	20.4	48.1	22.2	7.4
4. After the laboratory, I like physics more	14.8	33.3	46.3	3.7	1.9
5. The laboratory experience promoted my interest in physics	7.4	16.7	55.6	13	7.4
6. The laboratory experience motivated me to study physics	7.4	35.2	46.3	3.7	7.4

7. The laboratory experience stimulated my curiosity towards physics	7.4	16.7	55.6	11.1	9.3
8. The experience with the laboratory helped me understand the importance of starting from the phenomena and then giving a theoretical explanation	9.3	9.3	61.6	11.1	9.3

The results showed in Table 7 reveal a general overall students' satisfaction for the remote experience.

Table 7. Percentages of the overall satisfaction with the experience.

	Not at all	Slightly	Moderately	Very	Extremely
1. I liked the experience with the physics laboratory	0	11.1	55.6	24.1	9.3
2. I would participate in a similar experience again	5.6	7.4	48.1	27.8	11.1
3. The online laboratory is useful to university and job orientation	5.6	13	37	31.5	13

5.3 Teachers' Satisfaction and Interest

Results showed (see Table 8) that teachers are satisfied with the remote laboratory topics, in terms of interest (TS6) and coherence with school program (TS1). Moreover, they appreciated that the online laboratory allowed students to concretely explore phenomena studied at school (TS7).

Table 8. Means and standard deviations of teachers' satisfaction.

Item	Mean	sd
TS1. The remote laboratory topics met my needs with respect to my subject curricula	4.33	.516
TS2. The remote laboratory facilitated the students' learning of the subject	3.83	.408
TS3. The activity carried out contributed to stimulating the students' interest	3.83	.408
TS4. The platform is simple enough that you don't need help to use it	2.83	.983

TS5. I think that for my students the use of Timeline was useful to learn laboratory topics	3.50	.548
TS6. The remote laboratory topics were interesting	4.50	.548
TS7. The remote laboratory allowed students to concretely explore phenomena studied at school	4.17	.408

Teachers answered to further questions regarding their laboratory practice at school (see Table 9). It should be noted that physics is not usually teach through practical activities in the laboratory or in the classroom, although nobody stated to teach physics only with formulas and theory.

Table 9. Frequencies of laboratory practice at school.

	Not at all	Slightly	Moderately	Very	Extremely
1. I teach physics at school also through laboratory practice	0	1	4	1	0
2. I carry out laboratory activities in class	0	1	4	1	0
3. I teach physics according to this scheme: expectations on a phenomenon, observation, comparison between expectations and experiment, theoretical explanation, collective discussion on the phenomenon and its explanation	0	0	2	2	0
4. I have ever proposed to my students to carry out an experiment in class to explain physics	3	2	0	1	0
5. I teach physics only with formulas and theory	2	2	2	0	0

Finally, results showed that teachers are satisfied with the remote laboratory, and they would like to participate in a similar experience in the future. Moreover, they affirm that the online laboratory is an activity very useful for university and job orientation (see Table 10).

Table 10. Frequencies of the overall satisfaction.

	Not at all	Slightly	Moderately	Very	Extremely
1. I have attended an online workshop in the past	2	4	0	0	0
2. Overall, I am satisfied with the experience	0	0	3	2	1
3. I would participate in a similar experience again	0	0	2	2	2
4. The online laboratory is useful to university and job orientation	0	0	0	1	5

6. Discussion and Conclusion

The challenge of providing high-level scientific experimentation opportunities to students serves to exacerbate the gap between school curricula and real-world scientific practices. This disparity can discourage students from pursuing higher education and careers in STEM fields. The European Committee of the Regions [47] has raised significant concerns regarding the misalignment between STEM workforce demands and enrolment rates in higher education. This misalignment is attributed to deficiencies in STEM education implementation across the European landscape. In particular, the Committee has identified three critical gaps within STEM fields: a shortage of qualified STEM educators throughout Europe, a notable decline in student interest in STEM disciplines, and an education system that often fails to align with the practical requirements of the labour market. To address these challenges, the Committee recommends the sharing of best practices in STEM education across institutions and regions.

This study aimed to evaluate the impact of remote laboratories on high school students' learning, satisfaction, and interest in physics. This discussion addresses the study's research questions, focusing on learning outcomes, satisfaction and interest, and future directions.

Regarding learning outcomes, the findings suggest that while there were no significant improvements in classical and quantum mechanics knowledge, variations were observed depending on the topic and school grade. For instance, students demonstrated a stronger understanding of the relationship between diffraction and electromagnetic waves. In contrast, final-year students encountered difficulties with mechanical waves, indicating possible misunderstandings that arose during either synchronous or asynchronous phases of the learning process.

These observations align with existing literature that suggests technology-enhanced interventions in educational settings often yield either no significant or only moderate impacts on learning outcomes [13].

However, it is important to note that the laboratory experience facilitated students' comprehension of fundamental physics principles and the scientific method, as evidenced by their interactions with researchers. This interaction highlights the critical role of engagement and communication in both educational and outreach initiatives, a point that has been well-documented in the literature [46].

When examining satisfaction and interest, the feedback from students and teachers regarding the remote laboratory experience was generally positive. Students and teachers appreciated the opportunity to explore physics phenomena within a realistic, real-world context. Such experiences not only enhanced the understanding of physics concepts but also sparked increased curiosity and motivation. Both groups recognised the potential of the remote laboratory experience as a tool for informing university choices and guiding future career aspirations.

Motivation remains a fundamental determinant in shaping career interests and decisions [48]. According to the Organisation for Economic Co-operation and Development [49], fostering motivation and interest during critical developmental stages—when students begin to contemplate their future careers—can lead to a higher number of students pursuing careers in science or science-based technology fields. In school environments where physics education is often confined to theoretical content, the remote laboratory offers a more practical approach. It enables students to engage with scientific processes directly and could consequently stimulate greater interest in STEM careers.

To enhance the user experience on the RIALE platform, both students and teachers have provided constructive suggestions. One key recommendation is to maximise the usability of the interface during asynchronous sessions, ensuring it is fully user-controlled and accessible. Additionally, improving the interface to increase the sense of immersion is seen as essential for fully realising the educational potential of remote experiments [38, 50]. Such enhancements would enable students to engage more deeply with the experimental process and foster a stronger connection to the scientific method.

Future research should focus on increasing response rates to strengthen data reliability and better assess the impacts of remote laboratories on student learning outcomes. Several challenges have emerged from this study. A significant obstacle was observed in teacher-mediated interactions, where researchers' attempts to maintain active and continuous participation from students during lectures were often unsuccessful. This interaction model highlights the need for strategies that sustain engagement and participation throughout the learning process, thereby integrating remote physics learning seamlessly into school curricula.

A potential solution to this challenge is to actively involve teachers in the design of experimental activities, positioning them as collaborators, researchers, or tutors. Such a role would allow teachers to guide students more effectively, fostering sustained engagement and deeper learning experiences.

In summary, despite certain limitations, the findings of this study offer valuable insights that could inform the development of innovative educational interventions aimed at integrating technology more effectively into scientific education. There is a clear need to enhance online educational tools and refine teaching methodologies. We recommend using the remote platform as a complementary resource for science and physics teachers. This approach would facilitate pedagogical strategies such as contextual learning, leveraging the interactions between students and the experimental setups manipulated by researchers to achieve specific outcomes at different stages of an experiment. It also includes adapting timelines to accommodate the integration of new scientific knowledge and allowing students to observe and interpret remote data directly from laboratory systems. Such interactions would enable initial interpretations based on their knowledge and curriculum context, strengthening the practical application of scientific concepts and processes.

CRediT author statement. Daniela Fadda: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Carole Salis**: Conceptualization, Methodology, Online strategy design, Resources, Writing - Review & Editing. **Matteo Tuveri**: Conceptualization, Methodology, Investigation, Writing - Review & Editing. **Carlo Maria Carbonaro:** Conceptualization, Methodology, Investigation. **Giuliano Vivanet**: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

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