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Comments, Reflections, Presentations, Reports, Debates, Interviews

About the Efficacy of Virtual and Remote Laboratories in STEM Education in Secondary School: A Second-Order Systematic Review *

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SULL'EFFICACIA DEI LABORATORI VIRTUALI E REMOTI NELL'EDUCAZIONE STEM PER LA SCUOLA SECONDARIA: UNA RASSEGNA SISTEMATICA DI SECONDO ORDINE

Abstract

Online laboratories brought new opportunities for instruction. In this work, a second-order systematic review about the efficacy of virtual and remote labs on learning in high school STEM education is presented. Nine systematic review and a meta-analysis were included. A descriptive summary (qualitative and quantitative) of their findings is provided. On average, online laboratories support learning to an extent comparable to that observed in real labs; their effect is even more positive when they are integrated into more traditional teaching practice (e.g., as pre-lab practice sessions before the hands-on experiments) and when they are supported by adequate teacher feedback. Content knowledge

* This study is the result of a collaboration between the authors. Within it, C. Salis is the author of paragraphs 1 and 2; D. Fadda is the author of paragraphs 3.1, 3.3, 4.1, 4.2.2, 4.2.3, and 5.1; G. Vivanet is the author of paragraphs 3.2, 3.4, 4.2, 4.2.1, 5.2. Here, the authors integrate and extend the analyses presented in Fadda & Vivanet, 2021.

is the learning outcome most often assessed; while practical and inquiry skills related to scientific reasoning are investigated less frequently. The results are promising for instructional design and for the future research, despite the data variability and some methodological limitations of individual studies (lack of relevant quantitative data, such as effect sizes and moderator analysis). Further experimental research is required to estimate the effect of online labs on different learning outcomes and to better understand the moderating role of some variables related to interventions and students.

Keywords: Online laboratory; Remote laboratory; Secondary school; STEM education; Virtual laboratory.

1. Introduction

STEM (Science, Technology, Engineering and Mathematics) education is a broad expression used to refer to an interdisciplinary curriculum aimed at developing scientific-technological skills. It is recognised as having a key role not only in the advancement of knowledge and technological innovation (Gonzalez & Kuenzi, 2012), but also as a foundation for successful employment and to sustain the national economy (National Academies of Sciences, Engineering and Medicine, 2018).

One of the fundamental aspects of scientific education lies in the practice of laboratory (e.g., Hofstein & Mamlok-Naaman, 2007). According to the National Research Council (2006, p. viii), laboratory is intended «as a place where students can practice scientific inquiry and reasoning, come to understand different kinds of knowledge claims that scientists make, and build their knowledge of science content». The instructional strategy based on laboratory experiences can involve a wide variety of teaching/learning activities characterized by the interaction of students with instruments and materials for observation and understanding of the natural world; and including the engagement of students in carrying out well-defined procedures for defining research questions, testing a hypothesis, designing an experimentation, and developing and discussing explanatory models.

Nevertheless, several factors can limit the use of laboratory at school, including the fact that usually they can only be used by a restricted number of students at a time; the high costs associated with their set-up and maintenance; the risks that are sometimes associated with an improper handling of substances and equipment (Hernandez-de-Menéndez *et al.*, 2019). Moreover, schools often face considerable obstacles to the use of laboratories due to inadequate and outdated materials, lack of funds for equipment renewal, as well as the general modernization of laboratories.

Considering the limitations mentioned above, it is worth noting that advances in technology lead to new opportunities for laboratory practice in school. Online labs can be used to replace, support and supplement traditional hands-on laboratories (Heradio *et al.*, 2016). It is an area of educational technology development of great interest, if one also considers that the global virtual and remote laboratories market estimated to be valued at USD 3.5 billion in 2020 and major growth is expected in the next years, reaching USD 8.8 billion by 2030 (DATAINTELO, 2022). Given these premises, in this study, findings from a second-order systematic review about the efficacy of online labs (virtual and remote) on learning in STEM education for high school students are presented.

2. Virtual and remote laboratories: definitions and initiatives

Many terms and definitions have been proposed to describe virtual and remote laboratories; however, there is no consensus in the literature on a common definition of them and their features. These are sometimes referred to as online labs, web-based labs, or computer-based labs; whereas when they are used jointly with each other or with traditional ones, they are sometimes defined as hybrid labs (Zapata & Larrondo, 2016).

Heradio *et al.* (2016) differentiate experimentation environments by two criteria: the way resources are accessed (remote or real/local) and the physical nature of the laboratory (simulated or real). The combinations of those criteria are represented in *Table 1*.

Table 1. – Experimentation environments by Heradio (2016).

	Local access	Remote access
Real resource	Hand-on labs	Remote labs
Simulated resource	Mono-user virtual labs	Multi-user virtual labs

Virtual labs allow students to access and conduct imitations of real experiments in a digital space. They represent a special category of simulations, through which students can manipulate virtual material and equipment on a computer screen via keyboard, mouse, or touchscreen (Zacharia *et al.*, 2015; Sypsas & Kalles, 2018). Scalise *et al.* (2011) propose a distinction between virtual labs and simulations of scientific phenomena. Virtual labs simulate on-screen the experiments that are traditionally performed in real laboratories by providing opportunities to use virtual materials, equipment, and tools that are designed to replicate those in an actual laboratory. Instead, simulations of scientific phenomena are used to model something that which is not easily observed in real life or are used in teaching situations where computer simulation offers other advantages (Scalise *et al.*, 2011, p. 1053). Generally, the objectives of virtual labs are to give a pre-real lab experience and an early introduction of concepts to familiarize users with a phenomenon or to substitute a real lab when the system to study is expensive, very large or too dangerous (Diwakar *et al.*, 2013).

Focusing our attention on virtual labs in STEM education for high school students, there are different relevant initiatives that have been carried out in recent years (Potkonjak *et al.*, 2016; Lynch & Ghergulescu, 2017), both in the more general STEM education (e.g., the Go-Lab Project [1]; Project ccSSe [2]) and in specific disciplines, mainly physics, chemistry and biology. They are available both as open-source software (e.g., Open Source Physics [3]; ChemCollective [4]; BioInteractive [5]) and proprietary software (Mirçik & Saka, 2018; Ali & Ullah, 2020).

Differently, remote labs allow students to observe and control science experiments in an interactive, experiential, real-time, online learning environment (Tho *et al.*, 2017). The distance between the user and the real experiment, mediated by technology, is one of the key-terms in their definition. Zacharia *et al.* (2015) refer to remote lab as a physical lab where all the material and/or the equipment are manipulated at a distance by computer technology. Similarly, according to Ma and Nickerson (2006, p. 6):

> what makes them different from real labs is the distance between the experiment and the experimenter. In real labs, the equipment might be mediated through computer control, but collocated. By contrast, in remote labs experimenters obtain data by controlling geographically detached equipment.

Also, with regard to remote laboratories, different initiatives in STEM education have been carried out and/or are under development (Lowe *et al.*, 2013; Heradio *et al.*, 2016), such as the WebLab [6] (García Zubía & Alves, 2012); the internet Schools Experiment System (iSES [7]: Schauer *et al.* 2005); the platform Riale [8] (Remote Intelligent Access to Lab Experiment: Salis *et al.*, 2021).

[1] https://www.golabz.eu/.
[2] http://www.vccsse.ssai.valahia.ro./main/index?lang=en.
[3] https://www.compadre.org/osp.
[4] http://www.chemcollective.org/.
[5] https://www.biointeractive.org/.
[6] https://weblab.deusto.es/website/.
[7] https://www.ises.info/index.php/en.
[8] https://riale.ideab3.it.

3. Method

3.1. *Objective and synthesis methodology*

The aim of this study was to collect evidence about the efficacy of virtual and remote labs on learning outcomes in high school STEM education. To this aim, a second order systematic review (without meta-analysis) was conducted to provide a descriptive summary (quantitative and qualitative) of the emerging results in secondary studies, highlighting findings that tend to converge, but also identifying those factors that can explain data variability (Becker & Oxman, 2008; Pellegrini & Vivanet, 2018).

3.2. *Eligibility criteria*

The studies selection was based on the following eligibility criteria:
- Intervention: only studies related to the effects of virtual or remote labs on learning outcomes in STEM education are included.
- Participants: only studies involving high school students are included.
- Research design: only systematic review (SR) or meta-analysis (MA) are included (excluding narrative synthesis).
- Measures: only studies reporting qualitative or quantitative assessment of learning outcomes (e.g., knowledge and understanding, practical skills, inquiry skills, analytical skills and scientific communication skills) are included.
- Timing and language: only studies published in English after the year 2000 are included.
- Publication status: only published works with full-text available, such as articles in peer-reviewed journals, chapters in books or conference papers are included (unpublished works were not considered).

3.3. *Information sources and search strategy*

A comprehensive literature search was carried out using the following electronic databases: ERIC, SCOPUS, and Web of Science. Moreover, references on literature reviews and meta-analyses, table of contents of thematic journals and Google Scholar were also hand-checked for additional references. Based on the objective of this study, keywords relating to online labs (e.g., remote lab, virtual lab, simulated lab, online lab), the learning outcomes (e.g., learning, achievement, knowledge, skills, motivation, attitude, satisfaction), and the domain (e.g., STEM, math, science, chemistry, biology, physics) were defined and then combined using logical Boolean operators.

3.4. *Selection and data collection process*

Firstly, duplicated occurrences were eliminated. Then, on the basis of eligibility criteria mentioned above, two independent authors carried out an initial screening based on the titles and abstracts of studies; and finally full texts of remaining studies were evaluated for final inclusion. After the screening phases, the selected studies were analysed for the data collection process. For each study, the following variables were coded: bibliographic reference (author, title, year and status of publication); type of secondary study (SR or MA), number and publication year of the primary studies included; type of intervention (virtual lab, remote lab, both of them); (iv) level of education; (v) learning outcomes; (vi) quantitative and qualitative results.

4. Results

4.1. *Study selection*

The selection process is represented in *Figure 1*. Among the 1013 references initially retrieved through the search strategy, ten secondary studies (nine SR and a MA conforming to the eligibility criteria mentioned above) were included, summarizing data from a total of 607 primary studies, published between 1978 and 2018.

4.2. *Results of individual studies*

The results of individual studies (*Tab. 2*) are presented in the following paragraphs, related to virtual labs (par. 4.2.1), remote labs (par. 4.2.2), and finally the comparison between the former and the latter (par. 4.2.3). They are mainly focused on, but not limited to, issues related to instructional design and teaching practice, learning assessment, online labs features, as well as research design. In case of studies investigating effects on different age groups, only results for high school students will be considered.

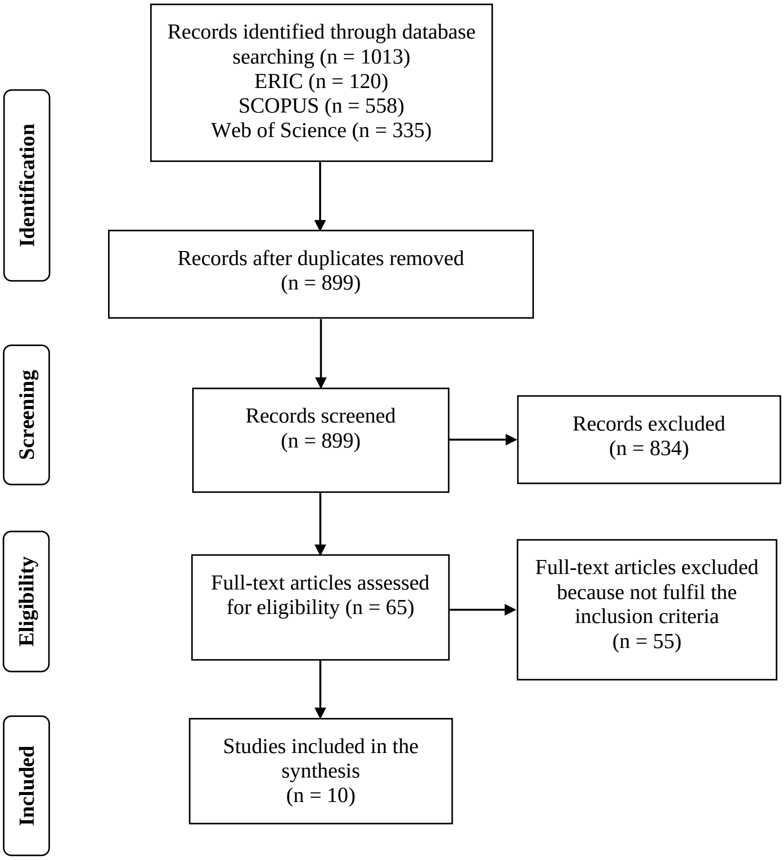

Figure 1. – Flow diagram detailing the screening process.

Table 2. – Studies included in the review.

Authors	Type of synthesis	N. (years) of primary studies	Type of laboratory	Level of education	Learning area
Scalise *et al.* (2011)	SR	79 (1995-2009)	Virtual	K6-12	STEM
Wang *et al.* (2014)	SR	42 (1990-2011)	Virtual & remote	K-16	STEM
Brinson (2015)	SR	56 (2005-2015)	Virtual & remote	K-12 & high education	STEM

Authors	Type of synthesis	N. (years) of primary studies	Type of laboratory	Level of education	Learning area
Zacharia *et al.* (2015)	SR	31 (2006-2015)	Virtual & remote	K-12 & high education	STEM
Brinson (2017)	SR	56 (2005-2015)	Virtual & remote	K-12 & high education	STEM
Tho *et al.* (2017)	SR	62 (1992-2014)	Remote	K-12 & high education	STEM
Sypsas & Kalles (2018)	SR	29 (*ante* 2018)	Virtual	K-12 & high education	Biology Bio-technology, Chemistry
Tsihouridis *et al.* (2019)	MA	106 (1978-2018)	Virtual	K-12 & high education	STEM
Rubim *et al.* (2019)	SR	99 (2003-2015)	Remote	K-12 & high education	STEM
Udin *et al.* (2020)	SR	47 (2010-2018)	Virtual	K-12 & high education	Biology Bio-technology, Chemistry

4.2.1. Virtual labs

Among the included studies, the efficacy of virtual labs on learning was investigated in three SRs and one MA. Scalise *et al.* (2011) focused their SR on virtual labs and simulations of scientific phenomena, mainly applied to physics (n = 48) and life sciences (n = 44). Half of the primary studies (n = 41) used a pre-post comparison to evaluate the effects on learning and reported a general positive impact of virtual labs. However, it should be noted that quantitative estimates of effect size are usually missing. Of the remaining studies, 33 were quasi-experiments, 13 case studies, and 8 did not fit into the previous categories (some studies appear in more than one study type). The authors described the design principles relating to the virtual labs and simulations interface (especially in relation to student attention) and visualization (e.g., zooming, alternative perspectives, control of speed) that appear most relevant for their efficacy, supporting learning and a positive perception of the lab. The authors also define some instructional principles for virtual labs, by identifying different levels of depth and complexity (from a basic one to an advanced one). They recommend encouraging the active investigation of the student starting from being able to identify the research problem and develop hypotheses; giving priority to evidence, making observations, and collecting data; formulating and evaluating explanations of results, even unexpected ones; learning to communicate and to justify results.

Sypsas and Kalles (2018) analysed in their SR the applications of virtual labs in biology, biotechnology, and chemistry education. Results showed that virtual labs are an effective supplementary tool supporting teaching in the classroom, with positive effects on knowledge, scientific reasoning, problem solving, critical thinking and motivation of students. Virtual labs resulted at least as effective as the traditional ones, promoting self-paced learning and increasing students' preparation for the final examination. Most of the studies (61%) used a blended learning method: advantages of virtual labs were found to be greatest when they integrate traditional teaching practice, for example, when used as pre-lab practice sessions to become familiar with the hands-on experiments. Moreover, in some cases, advantages arise from the possibility of carrying out experimentation otherwise not always possible in real-world settings (e.g., dissection) or from the possibility of visualizing digital representations of chemistry concepts.

Udin *et al.* (2020) investigated the application of virtual labs in biology through a SR. The results, characterized by a wide variability, showed that virtual labs integrated by practical activities are more effective than traditional or virtual laboratories alone. Traditional labs are a better environment for student interactions and collaboration; while virtual labs have significant positive effects on the ability to perform a correct experimentation activity. The most investigated learning outcome regarded conceptual understanding and the greatest improvements in understanding biology was observed on the low-performing academic students. The authors noted that positive effects on comprehension appear when virtual labs are supported by other learning media like appropriate textbooks and equipment; even if some students seem to be uninterested if problems are presented in a virtual lab and prefer real life representations.

Finally, Tsihouridis *et al.* (2019), in the only meta-analysis included, investigated traditional and virtual labs in natural sciences. Data show a significant relationship [χ^2 (4) = 13.289, p = 0.039] between educational level and experimental interventions. Real labs display better learning outcomes with primary school children (35.7%), higher education students (14.9%), and finally students of secondary education (6.9%). Instead, virtual labs display better learning outcomes with tertiary level students (44.7%), followed by secondary level ones (31%), and finally primary students (14.3%). Concerning high school students, in 62% of cases, traditional and virtual laboratories display similar learning outcomes. Virtual experiments stimulate the interest of students, but when researchers asked their participants about their preferred type of lab, regardless of learning outcomes, results showed that students prefer the combination of the two labs. Concerning directions for research, the authors observe a growing trend of learning studies involving virtual environments, from primary to secondary education, probably resulting from the gradual integration of new technologies in schools.

4.2.2. Remote labs

Among the included studies, the efficacy of remote labs on learning was investigated in the following two SRs. Tho *et al.* (2017) focused their attention on science education and found a prevalence of empirical studies in physics, conducted on small samples (n < 200; 85%), with a non-experimental design (n = 16) and quantitative methods for data analysis (n = 18). None of the studies reported the effect size and most of the experimental studies did not explicitly state the number of participants in the control and experimental groups. In four studies remote experiments appear to be an alternative learning experience or supplement to traditional labs. Results related to conceptual understanding are normally collected via conceptual tests (n = 17), and the questionnaire is frequently used to measure attitudes, such as enjoyment, satisfaction, motivation, and confidence (n = 16). Although remote labs present advantages in terms of design, sense of reality, interest, usability and usefulness, the authors point out some limitations, such as issues related to access (system crashes) and Internet connection. Authors reported that gender received little attention: one study did not find significant differences and two studies did not test gender differences due to the limited number of girls.

Rubim *et al.* (2019) conducted a comprehensive analysis comparing remote labs with traditional ones. After an initial description of the characteristics of the studies, the authors examined the advantages/disadvantages of remote experimentation, as well as the server and client technologies. Several primary studies showed that learning results reached by students are the same or higher in remote labs compared to the traditional ones in all outcome categories: knowledge and understanding, practical skills, inquiry skills, analytical skills, perception, and social and scientific communication. Concerning the main technologies, on the server side, there is extensive use of LabView (due to its availability and user-friendly language) and, on the client side, of the Java Applet (due to its popularity and independence from the operating system).

4.2.3. Virtual and remote labs

four SRs compared virtual and remote labs. Wang *et al.* (2014) included forty-two studies (all reporting empirical data, including experimental designs, exploratory studies, and case studies) concerning the use of virtual and remote labs in physics (n = 18), chemistry (n = 15), and biology (n = 10). Positive effects on learning for both types of labs were found with a certain variability. Most studies reported students' cognitive processes as their major outcomes (n = 41), such as conceptual understanding, manipulating variables, visualizing data or scientific phenomena. Cognitive outcomes were often integrated with the measurement of the students' attitude (n = 22), mostly relating to satisfaction, interest and preferences for the technologies used, rather than motivation towards the scientific discipline. Few studies considered psychomotor skills (e.g., operational, graphing, visualization skills; n = 4) and skills necessary to carry out a complex task such as reasoning and scientific investigation (n = 5). Authors find that virtual simulations or manipulations promote learning (knowledge and cognitive processes) and the positive perception of technology, especially when combined with physical laboratory activities. Remote labs, although effective for learning, require further empirical evidence as they are less studied than virtual ones. Studies mainly reported short-term interventions with students invited to work in small groups (n = 23) or individually (n = 18) with the help of computers. Finally, although teacher training (in terms of technological and pedagogical competence) can significantly improve the quality of learning in the laboratory, authors found that this factor is not adequately investigated in the selected studies.

Brinson (2015) in his SR summarized fifty-six empirical studies comparing learning outcomes in traditional (control group) and online (virtual and remote; experimental group) laboratories. Authors found evidence of comparable (n = 14) or higher (n = 36) learning outcomes in online labs than traditional ones. Almost all the studies measured the knowledge and understanding of the students (95%; n = 53) and 87% (n = 46) of them provided evidence of the same or greater results in online labs compared to traditional ones. Other learning outcomes were considered: inquiry skills (7%; n = 4), practical skills (16%; n = 9), perception (53%; n = 28), analytical skills (15%; n = 8), social and scientific communication skills (9%; n = 5). Almost all studies measured students' learning outcomes with traditional quizzes or exams (n = 40) rather than with other assessment tools such as practical exams (n = 5) or laboratory reports (n = 5). The author proposes the KIPPAS model to categorize learning outcomes: knowledge and understanding of theoretical concepts; the ability to investigate and develop scientific reasoning; practical and equipment management skills;

the interest in science; analytical skills to predict, criticize, integrate, and interpret data; social and scientific communication in term of teamwork as well as the ability to summarize and present experimental data.

Zacharia *et al.* (2015) conducted a SR of thirty-one studies, focusing the attention on the types of guidance used by the teacher for supporting student in the use of online labs. Authors classified guidance in performance dashboard (adapt individual inquiry behaviour by providing information on its results and processes); process constraints (reduce or restrict unnecessary student activities); heuristics (suggest what to do); prompt (give students specific indications on what to do); scaffolds (provide structures to perform a task that would otherwise be beyond their capabilities); direct presentation of information. Each guidance identified (n = 89) provides a personalized support in a specific inquiry phase: orientation, conceptualization, investigation, conclusion, discussion. Guidances were used extensively in two or more phases to guide the students' learning process (n = 31 in total), reporting a positive impact on learning in most cases (n = 17). Investigation is the phase with the higher number of guidances identified (n = 27); during this latter, numerous heuristics (n = 13) are provided, for example, to confirm hypotheses, manage extreme values, make a graph, and interpret unexpected findings.

Brinson (2017), in a subsequent publication, investigated further factors (e.g., participants' nationality, demography; scientific discipline and research methodology) relating to the comparison between virtual and remote labs (experimental group) with traditional ones (control group). The field of natural sciences (n = 46) is especially represented with studies in physics (n = 19; 34%), biology (n = 14; 25%) and chemistry (n = 12; 21%). Only two virtual lab studies examined gender differences and few studies analysed previous knowledge/experience or learning style (n = 7) to evaluate its influence on learning. Most studies use quantitative (n = 44) rather than qualitative (n = 12) research methods. 86% of quantitative studies use inferential statistical analysis to evaluate laboratory reports, written assignments, tests, quizzes, exercises and/or course grades.

5. Synthesis and conclusions

5.1. *Synthesis of quantitative data*

Because of the type of individual studies retrieved, including only one meta-analysis, and the consequent lack of effect sizes or other relevant quantitative data, it was not possible to carry out a comprehensive secondary statistical analysis. Therefore, here a quantitative analysis is introduced, limited to those variables investigated in at least more than one study and for which quantitative data (percentages) were available, namely the learning outcomes, the assessment strategies, and the research design. When percentages were not available, they were calculated on the basis of reported frequencies; then we used the mean percentages for the comparison of results.

With reference to the learning outcomes (*Tab. 3*), results show that on average online labs were equal (43%) or more effective (48%) than the traditional laboratories; only 11.5% of results showed higher learning achievement in real labs. However, it should be considered that Brinson (2015) included undergraduate students in his analysis; indeed, Tsihouridis *et al.* (2019), that reported data disaggregated by education level, found that virtual labs/simulations are particularly effective in higher education.

Moreover, with reference to the effects on learning, it is worth noticing that available data do not allow to estimate the possible incidence of publication bias, a risk occurring when the research that appears in the published literature is systematically unrepresentative of the population of completed studies (Rothstein & Hopewell, 2009). Meta-analyses use statistical procedure to estimate the publication bias, but results reported in the studies do not allow to measure the actual incidence of this latter.

Table 3. – Learning outcomes[9].

Variables	Authors	Gains	Mixed results	No gains
Overall learning gains	Scalise *et al.* (2011)	71%	25%	4%
		Higher in online	Equal	Higher in real
Online vs real labs	Brinson (2015)	65%	24%	16%
	Tsihouridis *et al.* (2019)	31%	62%	7%
	Mean	48%	43%	11.5%

Concerning assessment strategies, *Table 4* shows that in the 94% of results reported, cognitive skills and knowledge was the outcome most frequently assessed, followed by attitude and perception (50%). Moreover, although

[9] In this table and those that follow, *Tabs. 4* and *5*, total may not equal to 100% because some studies report results attributable to more than one category.

practical and inquiry skills (i.e., developing scientific reasoning and understanding of the nature of science) are essential in STEM education and laboratory practice, both of them are not often taken into account (respectively 10% and 13%).

Different strategies and tools to assess learning outcomes were reported by several authors, but the exam/test is the most frequently assessment technique (73%), followed by questionnaires (43%), generally used for data collection about attitudes towards laboratory practice. These data are similar across all studies supporting the consistency of the results. It should be noted that, even if learning outcomes and assessment tools varied considerably, almost all studies focused the evaluation on cognitive learning results, measured by tests, and about half of them assessed students' perceptions of the laboratory experience by means of questionnaires. Few studies used alternative assessment tools to better understand students' reasoning and meaning construction.

Table 4. – Assessment strategies.

Variables	Authors	Cognitive/ knowledge	Attitude/ perception	Practical/ psychomotor	Inquiry
Outcome	Wang *et al.* (2014)	98%	52%	9.5%	5%
	Brinson (2015)	95%	53%	16%	7%
	Tho *et al.* (2017)	88%	46%		19%
	Mean	94%	50%	13%	10%
Measure		Exam/test	Questionnaire	Lab report	Grade
	Brinson (2015)	71%	40%	9%	11%
	Tho *et al.* (2017)	74%	46%	22%	17%
	Mean	73%	43%	16%	14%

Finally, concerning research design (*Tab. 5)*, different approaches are adopted in the selected studies; the quasi-experimental and the non-experimental design are the more frequently used, compared with a pre-post experimental design with a random selection of participants (45%). On average, 74% of studies used quantitative method for data analysis (descriptive statistics, such as means and frequencies, or inferential statistics, as t-tests, correlation and regression); less than 10% of them conducted qualitative analysis; while 20% of them integrated quantitative and qualitative methods.

Table 5. – Research design.

Variables	Authors	Experimental	Quasi - Non experimental	
Study design	Scalise *et al.* (2011)	52%	70%	
	Tho *et al.* (2017)	38%	62%	
	Mean	45%	66%	
Method for data analysis		Quantitative	Qualitative	Mixed
	Brinson (2017)	79%	9%	12%
	Tho *et al.* (2017)	69%	4%	27%
	Mean	74%	7%	20%

5.2. *Synthesis of qualitative data*

Despite the variability of data and the methodological limitations previously mentioned, the results of individual studies are promising for practice and future research. With reference to the implications for instructional design and teaching practice, the selected studies converged on the substantial comparability of the effects between online and traditional laboratories on learning. Students in virtual and remote laboratories tend to achieve comparable outcomes (Wang *et al.*, 2014; Sypsas & Kalles, 2018; Tsihouridis *et al.*, 2019) or even better than those obtained in traditional labs (Brinson, 2015, 2017; Rubim *et al.*, 2019). It should be noted that in most of the selected studies, knowledge and understanding are the most frequently evaluated objectives (Brinson, 2015; Udin *et al.*, 2020; Wang *et al.*, 2014).

The use of online labs is significantly improved by integrating practical activities. Virtual labs can be used as a preparatory environment for real school experiments, providing a first experience of familiarization with laboratory practice (Sypsas & Kalles, 2018); the remote labs can constitute a valid experience as an addition to practical work (Tho *et al.*, 2017),

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although, online labs cannot completely replace real labs (Rubim *et al.*, 2019; Udin *et al.*, 2020). Indeed, a hybrid learning strategy is more effective and preferred by students than the sole use of traditional or virtual laboratories (Wang *et al.*, 2014; Sypsas & Kelles, 2018; Tsihouridis *et al.*, 2019; Udin *et al.*, 2020).

In addition, available data show the positive effects of online labs (Brinson, 2015; Udin *et al.*, 2020) to the ability of conducting experiment procedures (e.g., application of protocols, measurement techniques, and use of instrumentation), particularly when the use of virtual labs is supported by adequate textbooks and physical equipment (Udin *et al.*, 2020).

Few studies investigated outcomes related to scientific inquiry skills, such as the definition of hypotheses, analysis of empirical evidence, corroboration and/or falsification of a hypothesis (Scalise *et al.*, 2011; Brinson, 2015), but the limited evidence available show that online labs supported equal or superior outcomes compared to traditional labs (Wang *et al.*, 2014; Brinson, 2015; Sypsas & Kalles, 2018).

The comparative analysis of results about non-cognitive dimensions shows that learning outcomes are associated with a positive perception by the students of the laboratory experience (Brinson, 2015; Tho *et al.*, 2017), while effects on motivation towards the scientific discipline was less investigated (Wang *et al.*, 2014).

Concerning instructional design, Scalise *et al.* (2011) underline the importance of a design framework associated with scientific inquiry. This approach follows a progression from basic to advanced principles into a set of subthemes (e.g., scientifically oriented questions, prioritizing evidence, communication, and justification of findings). It is important to note that a key factor for effective laboratory practice appears to be related to the teacher's feedback. Although technological features, such as the digital interface, may facilitate students' learning (Scalise *et al.*, 2011), the effectiveness of online labs would not be attributable to the technology itself, but rather to the guidance by the teacher and the interactions with this latter (Zacharia *et al.*, 2015). Teachers can support students in the conceptualization and investigation phases with different heuristics (e.g., how to interpret unexpected findings) and scaffolds (e.g., tools for data interpretation; dynamic testing scaffold), for instance supporting students in the definition of research questions and hypotheses for their experiments (Zacharia *et al.*, 2015). The issue of teacher training for the effective use of laboratories was already strongly emphasized by the National Science Teachers Association (NSTA, 2007), and it is also consistent with the literature regarding the effectiveness of digital technologies on learning at school (Higgins, Xiao, & Katsipataki, 2012). However, despite the evidence on the central role of teaching practice in the use of online labs, this issue does not appear to receive sufficient attention in the studies considered (Wang *et al.*, 2014). Teachers should learn how to use feedback effectively, how to support an inquiry-based process, how to encourage students to ask questions and solve problems, by means of the scientific reasoning. Stimulating students' interest and comprehension during this process promotes learning, but also critical thinking, curiosity, and motivation (Chatterjee, 2021).

With reference to intervention characteristics, it should be noted that most studies were short-term interventions on small samples (Wang *et al.*, 2014) and that there is a lack of follow-up measures, which does not allow us to evaluate the persistence of learning. Finally, although smartphones, tablets and interactive whiteboards are becoming increasingly popular in classrooms, the computer remains the most widely used support for scientific laboratories (Wang *et al.*, 2014).

Regarding the future research, several elements require further investigation. Firstly, future studies should investigate the effect of online labs on different learning outcomes (Wang *et al.*, 2014), such as the scientific reasoning (Scalise *et al.*, 2011; Brinson, 2015) and practical skills (Wang *et al.*, 2014; Brinson, 2015; Udin *et al.*, 2020). Further studies are also required to better understand the moderating role of intervention (e.g, individual, cooperative, or collaborative strategy; its structure and the duration) and students' characteristics (e.g., gender, learning style and previous knowledge) that may influence learning outcomes (Brinson, 2017; Tho *et al.*, 2017). In addition, research should further investigate which elements of real laboratories can be replaced, or cannot be replaced, or supplemented with online lab (Wang *et al.*, 2014). Furthermore, it is necessary to collect more reliable results about the effects of virtual and remote laboratories on motivation toward science because this latter is considered a stronger predictor of achievement, persistence on a task and scientific career aspirations (Wigfield & Eccles, 2000).

With reference to the research design, the methodology used varied from experimental to non-experimental design (Scalise *et al.*, 2011; Wang *et al.*, 2014; Tho *et al.*, 2017). In most of the studies, testing the cause-effect relationship between the independent (virtual and remote labs) and dependent (learning outcomes) variables was not possible. The lack of quantitative data related to effect size forced researchers to use techniques of SR, rather than MA to test the study hypotheses (Scalise *et al.*, 2011; Wang *et al.*, 2014). Only the MA by Tsihouridis *et al.* (2019) provided quantitative evidence regarding the effectiveness of virtual labs compared to traditional ones. In addition, it was observed that some experimental studies did not clearly report the number of participants in the experimental and control groups (Tho *et al.*, 2017), threatening the external validity of conclusions. For these reasons, further experimental research is required to collect more reliable evidence to support the promising results emerging from this second-order systematic review.

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Riassunto

I laboratori online rappresentano una nuova opportunità per la didattica. In questo contributo, si presenta una revisione sistematica di secondo ordine sulla efficacia dei laboratori virtuali e remoti sull'apprendimento nelle discipline STEM nella scuola secondaria. Nove revisioni sistematiche e una meta-analisi sono state incluse e una sintesi descrittiva dei loro risultati (qualitativi e quantitativi) è presentata. Mediamente, i laboratori online risultano supportare l'apprendimento in misura comparabile ai laboratori fisici; specialmente quando integrati in attività laboratoriali tradizionali (es. come sessioni di pratica preliminari a un esperimento reale) e quando ben supportati dal feedback dell'insegnante. La conoscenza è l'obiettivo di apprendimento più indagato, mentre meno dati sono disponibili sulle competenze pratiche laboratoriali e di ragionamento scientifico. I risultati sono promettenti sia per la progettazione didattica sia per la ricerca futura, nonostante la variabilità dei dati e le limitazioni metodologiche riscontrate (scarsità di dati quantitativi rilevanti, in particolare per il computo degli effect size e dell'effetto di variabili moderatrici). Ulteriori indagini sperimentali sarebbero necessarie per stimare gli effetti su differenti obiettivi di apprendimento e per comprendere il ruolo moderatore di fattori legati alle caratteristiche degli interventi e degli studenti.

Parole chiave: Educazione STEM; Laboratorio online; Laboratorio remoto; Laboratorio virtuale; Scuola secondaria.

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