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# Collaboration in virtual and remote laboratories for education: A systematic literature review

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## Abstract

Hands-on laboratories are essential to acquire skills in education. However, they can be costly, lack flexibility, and do not allow one to do an unlimited number of experiments. Virtual and remote laboratories represent an interesting alternative to traditional hands-on lab sessions. On the other hand, fostering collaboration between learners and between learners and teachers is an important aspect to develop in these virtual and remote laboratories, as it enhances learning. This systematic literature review presents an extensive overview of previous research about fostering collaboration in educational virtual and remote laboratories. Results of this study show that communication and group awareness tools are generally well integrated into remote and virtual laboratories. These tools foster collaborative learning as they enable users to communicate, to be aware of the presence and the actions of the other members of the group and to share knowledge. However, tools for guiding and regulating collaboration are poorly integrated in the laboratories. These tools are yet useful to foster collaborative learning as they respectively give instructions to collaborate effectively and information about the state of collaboration to regulate it. This review also identified a minority of studies that assessed the quality of collaboration and learning in laboratories. Future research should put more emphasis in investigating guidance and regulation tools, as well as integrating studies to evaluate collaboration and learning in educational remote and virtual laboratories.

**Keywords** Computer-supported collaborative learning · Educational remote laboratories · Educational virtual laboratories

## Introduction

Hands-on laboratories play an important role in education, particularly in STEM (Science, Technology, Engineering, and Mathematics) curricula, by allowing students to learn meaningfully and better understand theoretical concepts through direct hands-on experience (Jiun et al., 2014; Ma & Nickerson, 2006). Being in line with the expectations of recruiters (Patacsil & Tablatin, 2017) and the objectives of physics laboratories in teaching by the American Association of Physics Teachers in 1997 (Corter et al., 2011), hands-on laboratories also enable the development of social and teamwork skills (Ma & Nickerson, 2006; Lindsay et al., 2007), since hands-on work is typically conducted in groups. Hands-on laboratories exemplify inquiry-based learning, a process grounded in socio-constructivist theories (Bell et al., 2009), which suggest that knowledge is built through collaborative processes and shared information among group members (Duit & Treagust, 1998). According to Bedwell

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et al. (2012), collaboration is a term with different definitions depending on the discipline. In our works, we adhere to the definition proposed by the Australian Council for Educational Research in 2020 (Scoular et al., 2020): "Collaboration refers to the capacity of an individual to contribute effectively in a group. This involves perseverance, contributing to team knowledge, valuing contributions of others and resolving differences. Effective collaboration involves a division of labour with participants who are engaged in active discourse that results in a compilation of their efforts." In education, a commonly accepted definition of collaborative learning is "a situation in which two or more people learn or attempt to learn something together" (Dillenbourg, 1999). It is therefore important to emphasize a key distinction between the concept of *collaborative learning* and the broader notion of *collaboration*: the former places specific emphasis on learning as its primary goal. While collaboration generally refers to contributions made within a group context (Scoular et al., 2020), collaborative learning specifically involves interactions between individuals that have the potential to activate learning mechanisms (Dillenbourg, 1999).

Despite the aforementioned benefits, hands-on laboratories have limitations. First, the ability of universities to fund these learning sessions is limited by the increasing complexity of experiments, giving students access to a restricted number of experiments (Richter et al., 2011). The large number of students also limits the availability of instruments (Muchlas & Novianta, 2015). Moreover, the variety of experiments can be limited for safety reasons, to reduce risks associated with students handling the equipment (Bochicchio et al., 2015b). One solution to overcome these limitations is to turn to virtual and remote laboratory (VRL). Govaerts et al. (2013) define VRLs as "remote laboratories, virtual experiments or data sets accessible from the browser through apps". A real laboratory enabled for remote access is referred to as a remote laboratory, while a real laboratory replicated or represented entirely through software is called a virtual laboratory (Potkonjak et al., 2016). Faced with some of the limitations of traditional laboratories, VRLs offer flexibility and independence, providing the opportunity to access equipment 24/7 (Richter et al., 2011). Additionally, the costs of VRLs are lower than those of hands-on laboratories (Barros et al., 2013; Hernández-de-Menéndez et al., 2019). Finally, extreme conditions, such as high or low temperatures, are easier and safer to model in a virtual lab than in a conventional one (Drysdale & Braithwaite, 2017).

Nevertheless, integrating collaboration into VRLs—similarly to hands-on laboratory environments—is essential. Several theoretical perspectives underline the centrality of collaboration in learning. For instance, Hutchins' theory of distributed cognition defines a cognitive system as extending beyond a single individual to encompass a group of people and the artefacts within their environment (Hutchins, 2000; Gier & Moffatt, 2003). Cognitive activities, from this viewpoint, are characterized by the "propagation of representational state across media" (Hazlehurst et al., 2008), meaning the circulation and transformation of information and knowledge within the system. In such collaborative settings, individuals draw upon each other's resources and knowledge to achieve shared objectives (Rogers, 1997). This group-based perspective aligns with the theory of social constructivism and Vygotsky's approach, which posit that learning occurs through experiential, communicative (Leinonen et al., 2000), and social processes (Vygotsky, 1978). Consequently, learning is understood as an active and inherently social activity (Leinonen et al., 2000). Peer interactions foster explanation, debate, and mutual regulation, all of which contribute to the co-construction of knowledge (Dillenbourg, 1999). Within VRLs, this collaborative dimension is especially relevant as it can yield diverse learning outcomes. For example, it can help learners develop inquiry-based skills (Saab et al., 2012), or lead to knowledge acquisition and improved problem-solving abilities during joint tasks (Dillenbourg, 1999). Moreover, collaboration is recognized as a

key factor in the effectiveness of laboratory-based learning technologies (Corter et al., 2011). Olson and Olson (2000) also highlight the importance of strong interpersonal bonds in determining the success of remote work. Therefore, embedding collaboration in VRLs is a critical strategy for engaging students and ensuring the effective deployment of this technology. Yet, VRLs pose unique challenges for collaborative learning. As reported by Corter et al. (2011), students working in remote laboratory environments require targeted support to collaborate effectively.

Integrating collaboration into virtual and remote laboratories therefore requires investigating the field of computer-supported collaborative learning (CSCL). CSCL is a field that involves many disciplines and consequently has a wide variety of theories and frameworks (Hmelo-Silver & Jeong, 2021) without a common definition (Stahl, 2021). However, Stahl (2021) proposes a prototypical design of CSCL which is the following: "The vision of CSCL advanced here is that students working in small groups can productively incorporate collaborative learning centrally in their schooling and in their intellectual development, taking advantage of appropriate forms of computer support."

From this, we can understand that the CSCL community is searching for optimizing the potential of computer support in order to facilitate collaborative learning.

Some researchers have investigated how to support collaborative learning in VRLs. However, prior works on this topic have developed solutions that hardly rely on CSCL frameworks and theories proposed by this community of research. In this paper, we study, through a systematic literature review, how CSCL is supported by the virtual and remote laboratories developed in the last decade. The overall objective of this review is to assess to what extent current VRLs support collaboration between students, as well as between students and teachers, to identify the gaps that remain to be addressed by future research in this domain.

## Related work

Prior research proposes a number of reviews on VRLs for education (Zhang et al., 2018; Chan et al., 2021; Roda-Segarra, 2021; Raman et al., 2022), but these studies do not focus on the support of collaboration within these learning environments. For example, Zhang et al. (2018) focused on the techniques used to implement collaborative virtual laboratories and identified different limitations, including issues related to the "feel of immersion, cost of system creation, and data acquisition methods" (Zhang et al., 2018). However, Zhang et al. (2018) did not explore the means by which collaborative virtual laboratories can support collaboration. Chan et al. (2021) carried out a systematic review of the literature focusing on virtual chemistry laboratories. They concluded that this type of virtual laboratory is a good complementary tool to hands-on laboratories, even though "learning theories or instructional support" have not been sufficiently incorporated into the instructional design (Chan et al., 2021). Roda-Segarra (2021) also conducted a systematic literature review about virtual laboratories during the COVID-19 pandemic. He highlighted the predominant use of videoconferencing tools in combination with other tools, and the limited use of immersive or virtual reality technologies for virtual laboratories, but did not focus his study on collaboration support (Roda-Segarra, 2021). Raman et al. (2022) wrote a review of the virtual laboratories covering the years 1991 to 2021, focusing their analysis on the institutional authors who designed these laboratories.

A few publications examine collaboration in educational VRLs in more detail (Potkonjak et al., 2016; Bhute et al., 2021; Oyarzun & Martin, 2023; May et al., 2023). Potkonjak et al. (2016) conducted a review of virtual laboratories based on four criteria for evaluation.

Among these criteria, the studied labs had to enable collaboration and communication among students and with the supervisor. In particular, the 4th criterion stated: "A 3D laboratory space must be created which allows for communication and collaboration among students and with the lab supervisor (or expert in the field)." The review identified limited compliance with this criterion—as well as with another—as a weakness among the labs examined. However, collaboration is only superficially addressed in this review. The latter focuses more on the laboratory space than on the implementation of collaboration and communication. Bhute et al. (2021) reviewed publications about VRLs, focusing particularly on their online collaborative aspect and related techniques, although their main focus seems to be on data sharing and communication between users. Nevertheless, one journal is exclusively dedicated to the topic of "Online Learner Collaboration" (Oyarzun & Martin, 2023), which is related to collaboration design in virtual environments and therefore more closely aligned with our subject matter, although virtual and remote laboratories are not specifically addressed. Finally, a review examined the design aspects of remote laboratories through social, technological, and pedagogical heuristics that include collaborative aspects (May et al., 2023). This study focuses on online laboratories in medical and dental education field as well as engineering and aviation fields. Although the analysis covers a wide range of application fields, only a small number of laboratories were studied. Moreover, it should be noted that the review is not systematic.

We found no systematic literature review specifically dedicated to supporting collaboration in educational VRLs. In light of these preceding examples, we therefore present a complementary approach in the form of a systematic literature review, which is specifically dedicated to collaboration support in VRLs for education.

## Research goal and research questions

The objective of this systematic literature review is to study the tools and techniques implemented in educational VRLs that facilitate and encourage collaboration among users. Additionally, this review aims to investigate how the quality of collaboration is currently assessed in VRLs. Therefore, three research questions have been identified:

RQ1: What are the learning areas and main properties of VRLs designed to support collaboration?

RQ2: What tools and features are integrated into VRLs to facilitate and enhance collaboration among users?

RQ3: What methods are used to evaluate the quality of collaboration and learning in VRLs?

By answering these questions, our objective is to guide designers of educational VRLs towards effective CSCL support.

## Identifying analysis criteria based on CSCL theories

In order to analyse current VRLs in terms of collaboration support, it is necessary to study the theoretical background on the cognitive and social mechanisms that produce effective collaboration, as well as the technical criteria associated with facilitation of these processes.

Collaborative processes involve multiple levels of analysis, including cognitive processes, individual characteristics, and collective behaviors (Bedwell et al., 2012). In the context of CSCL, online collaborative tools (Hernández-Sellés et al., 2019), as well as learning tools

and strategies (Chen et al., 2018) all play pivotal roles. A central challenge in designing collaborative learning environments is fostering effective interaction among students, teachers, and content (Hernández-Sellés et al., 2019), while also supporting meaningful learning through well-designed affordances. Such affordances have the potential to promote collaborative learning (Jeong & Hmelo-Silver, 2016) by helping groups develop and maintain the necessary skills and processes.

A number of studies have emphasized the importance of **communication** in both collaboration and collaborative learning processes (De Prada et al., 2022; Meier et al., 2007; Mateescu et al., 2019; Chen et al., 2018). Communication can be defined as "the global exchange of clear, precise information" (De Prada et al., 2022) and includes the common grounding process. Common ground refers to the knowledge and context that we have in common with others, and that we know we have in common (Olson & Olson, 2000). Therefore, communication support was mentioned by Jeong and Hmelo-Silver (2016) as an important affordance to consider. The meta-analysis of Chen et al. (2018) also mentioned computer-mediated communication as a tool used in CSCL to support learners' interaction. Communication can be synchronous or asynchronous, and take different forms such as text chat or videoconferencing (Jeong & Hmelo-Silver, 2016).

Coordination (Meier et al., 2007; Mateescu et al., 2019) and mental collaboration scripts (Schnaubert & Vogel, 2022) are also important aspects of collaboration. Coordination refers to the management of resources and tasks sequences (Meier et al., 2007). Mental collaboration scripts also refer to task management, corresponding to mental blueprints of interactions, roles and tasks between group members. To illustrate, in a hypothetical chemistry laboratory setting, a group member could imagine a mental collaboration script in which she assumes responsibility for the transfer of a substance into a flask, while the other assumes the role of recording observations in the laboratory notebook. Regarding the notion of coordination and mental collaboration scripts, Jeong and Hmelo-Silver (2016) identified the structuring of collaborative learning processes as an affordance to be taken into consideration. Indeed coordination and collaboration processes are not always obvious; students may be interested in tasks unrelated to the purpose of the collaboration, or unwilling to participate (Jeong & Hmelo-Silver, 2016). The structuring of collaborative learning processes can take the form of what we can call computational CSCL scripts. This type of **computational scripts** is designed to structure collaboration by "defining sequences of activities, by creating roles within groups and by constraining the mode of interaction among peers or between groups" (Dillenbourg & Tchounikine, 2007). This form of guidance, when used to support students' social interaction, assists them in overcoming superficial discussion and, consequently, fosters deep reflection within the context of CSCL (Chen et al., 2018). Moreover, online collaboration can increase the cognitive load of novice engineering students and consequently their performance in collaborative problem-solving during virtual experimentation activities. Computational collaboration script can help to reduce their cognitive load (Du et al., 2023).

Schnaubert and Vogel (2022) also proposed **group awareness** as another psychological prerequisite for successful collaborative learning. Group awareness refers to an understanding of the activities of others, an awareness of group dynamics and characteristics. This awareness is an essential prerequisite for the co-construction of knowledge within a CSCL context (Chen et al., 2018). For example, in the hypothetical chemistry laboratory setting, the group member responsible for writing the report can make sure that her partner pours the required amount of product into the flask, thus demonstrating group awareness. Establishing group awareness can be supported by tools integrated into CSCL environments. It can take the form of a feedback regarding past performance (Strauß & Rummel, 2023) or the form of a tool for visualizing

the distribution of participation as a bar graph for example (Strauß & Rummel, 2021, 2023). These group awareness tools improve the group's efficiency by providing information about how the group works (Kirschner et al., 2018).

Finally, **regulation** has been outlined as an important skill for successful collaboration (Schnaubert & Vogel, 2022; Hesse et al., 2015). Schnaubert and Vogel (2022) consider self-regulation in particular, whereas Hesse et al. (2015) refer to social regulation. Self-regulation can be defined as a form of metacognition, evaluation and personal adaptation of one's own learning process (Schnaubert & Vogel, 2022). In contrast, social regulation is associated with the capacity for recognition and mitigation of biases that can potentially impede group work (Hesse et al., 2015). We can group these notions together into an overall notion of regulation, which refers to efforts to adapt and metacognise one's processes and biases in relation to the group. To illustrate, in the hypothetical chemistry laboratory setting, if one member of the group realizes that she is participating much more than her peers, she can then give the floor to her partners, thereby demonstrating regulation. Regulation can also be encouraged by regulation tools, for instance through a combination of visual feedback on participation distribution and adaptive collaboration prompts (Strauß & Rummel, 2021) or through a tool which displays questions to scaffold the group planning (Järvelä et al., 2015). In the context of collaborative learning, feedback may also come from the teacher who then supports the collaboration process of the students (Chen et al., 2018). This assistance fosters the development of ideas, the building of knowledge and the motivation of students (Chen et al., 2018).

While the tools previously discussed have shown positive effects on collaborative learning, it is essential that they be contextualized within their academic discipline. Disciplinary context affects learning goals, which can be broadly categorized into three types: cognitive, intrapersonal, and interpersonal (Chen et al., 2018). Cognitive objectives typically focus on enhancing problem-solving skills aligned with task demands, and their specific nature varies by discipline. These goals may involve programming in computer science (Arora et al., 2017), instrument control in networking (Carreón et al., 2018) or biology (Bochicchio et al., 2016), or data analysis in fields like electronics (Callaghan et al., 2013) or astronomy (Aimran Wan Mohd Kamil et al., 2019). In contrast, interpersonal goals emphasize social competencies such as discussion, planning, and knowledge co-construction (Chen et al., 2018). As a result, tools supporting collaborative tasks may differ according to the discipline, although the needs in terms of interpersonal objectives remain relatively similar.

It is essential to provide learners with the necessary tools and affordances to facilitate collaborative learning. However, it is also crucial to evaluate the quality of the collaboration and learning to ensure that the implemented tools are effectively reaching their intended objectives. Data collection and analysis in VRLs is of real interest, for example to better understand performance during collaborative activity or to facilitate teaching based on the information obtained (Birkeland et al., 2023).

## Methodology

### Search strategy

We conducted this literature review following PRISMA guidelines (Moher et al., 2009). PRISMA is a set of evidence-based guidelines designed to improve the reporting of systematic reviews and meta-analyses. It provides a standardized framework that helps researchers

clearly and transparently report their methods, findings, and interpretations, making it easier for others to assess the quality and reproducibility of the reviews.

The search was conducted in March 2025 with 5 databases: ACM, IEEE, Springer, ScienceDirect and Web of Science. We searched for papers using the following query on paper's titles and abstracts:

(collaborat\*) AND ("virtual lab\*" OR "remote lab\*" OR "online lab\*" OR "web-based lab\*")

This query worked directly on Web of Science. For other databases, we had to split this query into several sub-queries in order to have a semantically equivalent search. We decided to restrict ourselves to publications between 2011 and 2025, with 2011 chosen as the starting point following the publication of Corter et al. (2011) of the same year. Indeed Corter et al. (2011) emphasized the need to study the improvement of a group's collective learning process in remote laboratories.

A total of 590 papers were initially retrieved, with 6 papers in ACM, 156 papers in IEEE, 63 papers in ScienceDirect, 15 papers in Springer and 350 papers in Web of Science. After removing duplicates, a total of 430 papers remained for screening.

## Coding process

A shared Excel spreadsheet was used to facilitate the coding process, which was conducted in three distinct stages:

1. The set of articles was evenly distributed among four coders. Each coder independently read and analysed the articles assigned to them.
2. In the second stage, each article was reviewed a second time by a different coder to ensure consistency and reliability of the coding.
3. Finally, a group discussion was held among all four coders to resolve any discrepancies and reach a consensus on the coded values.

No additional tools or natural language processing (NLP) software were employed during this process.

## Inclusion and exclusion criteria

We set inclusion and exclusion criteria to filter the articles and keep only those relevant to our research. These criteria are listed in Table 1. After screening with inclusion and exclusion criteria, 62 papers were retained and 368 were eliminated. It should be noted that during the screening stage, the readings were cross-referenced in order to reduce bias. Figure 1 shows the different stages of our systematic review (following the PRISMA template of Page et al. (2021)).

## Analysis criteria

We analysed the 62 articles by coding the relevant analysis criteria, which were grouped into categories and listed in a spreadsheet. By analyzing the articles based on these criteria, we aim to answer the research questions raised. The following sections present the categories of analysis criteria selected for our analysis.

**Table 1** Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed conference or journal paper or book chapter	Not a scientific publication
The full text of the study is available	Paper shorter than four pages
Paper written in English	Review
Publication in the field of education	No VRL presentation
Information about collaboration in a VRL	VRL without collaboration support
	Work in progress

## System

We began with a category of analysis criteria called "System". The aim of this category is to describe the virtual or remote laboratory presented in each publication. The analysis criteria "Discipline" indicates the discipline concerned such as Chemistry, Physics, Electronics, etc. The "Lab Type" criterion indicates whether the studied laboratory is remote, virtual, or both. Figure 2 illustrates a virtual and a remote laboratory. In the virtual laboratory example illustrated in Fig. 2a, virtual containers and machines can be manipulated by a virtual hand, which is controlled by the learner, whereas in Fig. 2b, it is rather a real instrument that is recorded and remotely operated through the interface.

The "Location" criterion defines whether users of the VRL are co-located, non co-located, or both. For example, a non co-located VRL could be used by a peer of students who are in their respective rooms, whereas a co-located VRL could be used by a peer in the same classroom. The "Temporality" criterion provides information about the synchrony of learners' work completion. Temporality is "synchronous" when users can be connected and perform actions together simultaneously. For example, this could be the case with a chemistry VRL where a student can fill a virtual flask in the laboratory at the same time as their partner is writing in the virtual report. The Temporality is "asynchronous" when users can perform actions on the application alone, without being connected to others. In the previous example, the temporality would be asynchronous if students could connect to the chemistry VRL and do their manipulations without waiting for the partner to connect. Temporality is "both" when both cases are possible. The "Lifetime" criterion is "permanent" when changes to resources are saved and the state of the lab is not reset from one connection to the next. The lifetime is "temporary" if the lab returns to its initial state each time the user logs in again. For example, an electronics laboratory would have a permanent lifespan if, after manipulating electronic circuit components and disconnecting, a student could reconnect to the laboratory at any time and find the electronic circuit in the same state as after modifying it. On the other hand, this laboratory would be temporary if, after reconnecting, the student found the electronic circuit in the initial state. If there is no information about the lifetime of the lab, we set it as "unknown". We also defined a "Dimension" criterion to indicate the dimension of the resources handled. The dimension is "2D" when the virtual resources are in 2D, "3D" when the virtual resources are in 3D, and "video" when users view the resources via video. Finally, the "Interaction trace" parameter indicates whether traces of user interactions with the laboratory are recorded ("yes" or "no"). For example, a laboratory could keep track of the time taken to complete a task, the number of attempts and the messages from a text chat.

Table 2 summarizes the analysis criteria of the "System" category we have chosen to include in our analysis.

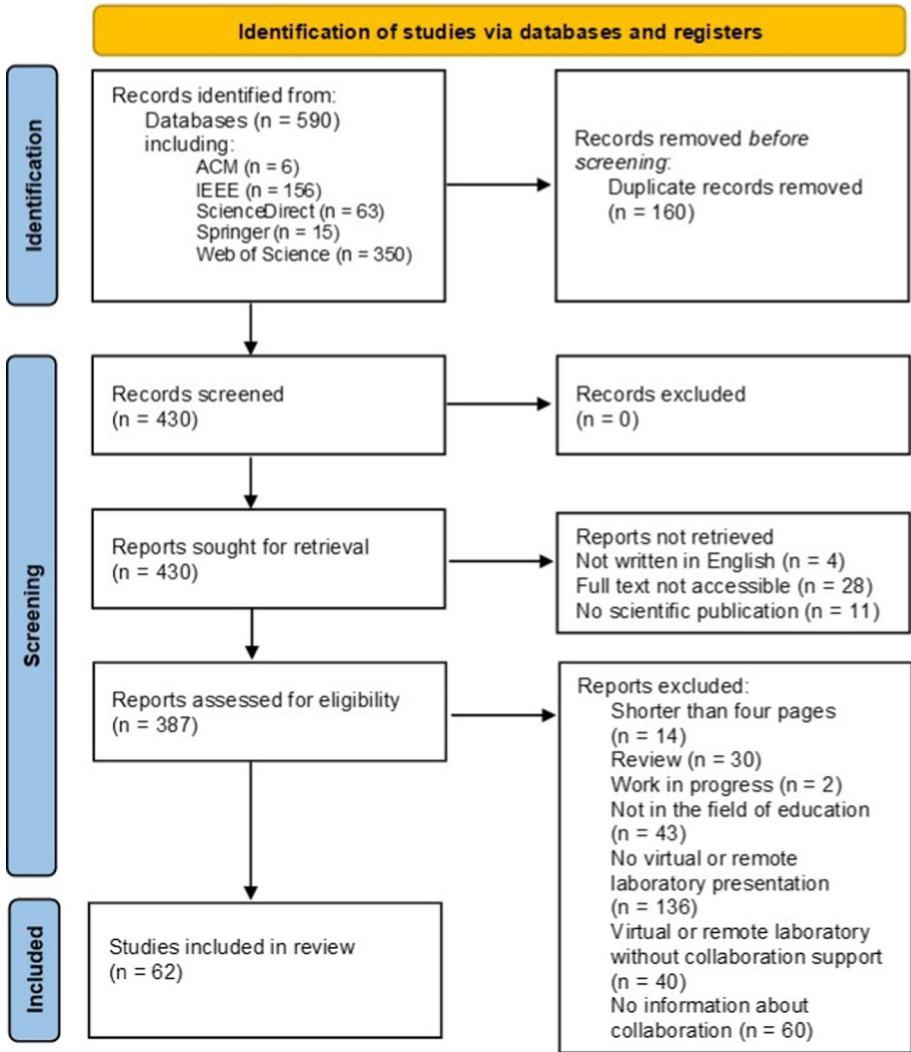
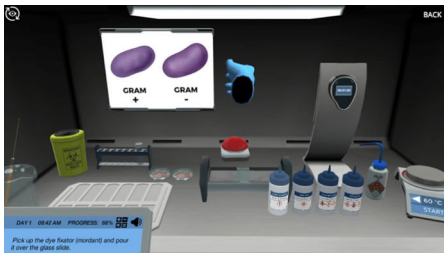
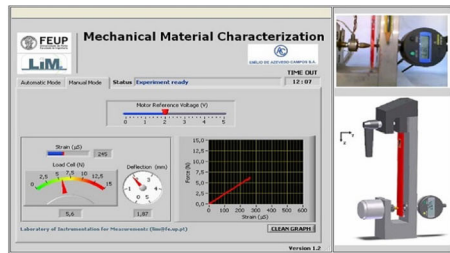


Fig. 1 Flow diagram representing the different phases of the systematic review



(a) Virtual laboratory (Tripepi, 2022)



(b) Remote laboratory (Restivo et al., 2009)

Fig. 2 Examples of a virtual laboratory and a remote laboratory

## Collaboration

To learn more about the contribution of VRLs to collaboration and to answer our research questions, we established a "Collaboration" category listing analysis criteria for analyzing collaboration. Within this category, we chose to study both the type of collaborative tasks in VRLs and the tools supporting collaboration within these VRLs.

First we established analysis criteria describing the type and form of tasks during collaboration in the analysed laboratories. The "Group size" criterion relates to the size of the group of students using the system, which can be "limited" by the application or "unlimited". The criteria "Collaboration between learners" and "Collaboration between learners and teachers" provide information about the presence or the absence of collaboration between these different types of users in the lab. The "Distinct roles between students" criterion, which can be "Yes" or "No", indicates whether learners have explicitly different roles in the lab. For example, one student may act as the manipulator while another acts as writer. The "Role assignment" criterion specifies how roles are assigned ("By the system", "By the learner", "By the teacher", "Several possibilities", "No role", "Unknown"). For example, the system could randomly allocate roles to group members and automatically change them for each question in the VRL. Alternatively, learners could choose their roles, or the teacher could predefine the roles for each group member. The "Task requiring several users" criterion is "Yes" if tasks within the laboratory cannot be completed without the participation of several users, and "No" if a single user could perform the task alone. For example, a virtual chemical engineering laboratory may have different tasks (machine operation and supervision) that need to be carried out simultaneously by different people, thus requiring several users.

Next, we established technical criteria to support effective collaboration in VRLs. These criteria were based on the findings described in the "Identifying analysis criteria based on CSCL theories" section of this paper. Following Jeong and Hmelo-Silver (2016), we defined "Communication" as an analysis criterion for VRLs. This criterion refers to the presence of communication tools within the system. Communication is "synchronous" when users can communicate in real-time, "asynchronous" when messages can be sent and received at different times, and "both" when both modes are possible. For example, communication is considered synchronous if a pair can interact in real time via a voice call within the VRL. In contrast, asynchronous communication could involve sending text messages to a partner or instructor who is not currently connected to the platform, but who would receive and respond to them later upon logging in—similar to how exchanges occur in a forum. The "Communication" criterion can also be "none" or "unknown" if there is no communication tool or if it is unknown. When possible, the type of communication is identified with values such as

**Table 2** System category

Analysis criterion	Possible analysis criterion values
Discipline	No preset value
Lab type	"Remote"; "Virtual"; "Both"
Location	"Co-located users"; "Non co-located users"; "Both"
Temporality	"Synchronous"; "Asynchronous"; "Both"
Lifetime	"Permanent"; "Temporary"; "Unknown"
Dimension	"3D"; "2D"; "Video"
Interaction trace	"Yes"; "No"

"audio", "text chat", "video", "other", "multiple artifacts" and "no type of communication" in the "Type of communication" criterion.

Inspired by the concept of collaboration scripts and structuring (Schnaubert & Vogel, 2022; Jeong & Hmelo-Silver, 2016; Dillenbourg & Tchounikine, 2007), we defined "Guidance" as a criterion for evaluating VRLs. Guidance tools support the establishment of mental collaboration scripts and collaborative activities by suggesting instructions or other actions. For example, according to our definition, CSCL scripts are guiding tools, although we do not limit ourselves to this technological solution for guiding collaboration. A guidance tool can, for example, guide students by describing actions to be carried out or by blocking certain functions while making others accessible. The "Guidance" criterion is "Yes" when an explicit guidance tool is integrated into the system, "No" otherwise. The "Type of guidance" criterion details how the system guides collaboration, whether through action blocking during the work session ("action blocking"), collaboration scripts ("script"), manual guidance by the teacher ("manual guidance by the teacher"), or manual guidance by the student ("manual guidance by the student"). For example, guidance by action blocking could take the form of a system that prevents a learner from clicking on a simulation to give his partner the opportunity to manipulate it. A collaboration script could consist of instructions asking one student to argue in favour of a solution and another student to argue against it. The teacher could guide the collaboration by prompting one student to explain their results to their partner. Finally, a student could guide the collaboration by giving each classmate the floor in turn. If another type of guidance is identified, the criterion can be "other". If no guidance tool is identified, the criterion is "no type of guidance".

We also drew on the concept of group awareness tools (Schnaubert & Vogel, 2022) to define "Group awareness" as a criterion for evaluating VRLs. This criterion refers to how the system makes user and group status information visible, accessible, and understandable. The "Group awareness" criterion can be "peer activities" if peer actions are made visible by the system, such as through notifications. It can also be "group performance" and "individual performance" if performance information is visible, for example, with a dashboard. Other possible values include "individual presence", "teacher presence" and "peer presence" which concern tools that make the presence of individuals, peers or teachers visible, such as displaying avatars. If a group awareness tool that does not make the presence, actions, and performance of others visible exists in the VRL, the criterion can be "other". If several group awareness artifacts are present, the criterion can be "several artifacts". When no group awareness tool is identified, the criterion is "none". The "Type of tool of group awareness" criterion provides more details about the group awareness tool in the lab.

We used the concept of regulation from Schnaubert and Vogel (2022) and Hesse et al. (2015) to define the "Regulation of collaboration" criterion. There is "Regulation of collaboration" when the system fosters regulation using specific tools. Collaboration can be "regulated at the individual level" when the system helps each person collaborate more effectively on a personalized one-to-one basis. It can be "regulated at the collective level", when the whole group receives information on how to work together more effectively. It can also be "regulated by the learners" when collaboration is regulated by the learners themselves, "regulated by the teachers" when collaboration is regulated by the teachers, "other" if regulated differently, and "no regulation". The "Type of regulation" criterion details how the system helps regulate collaboration. For example, the system can send individual notifications to alert users to over- or under-participation ("regulated at the individual level"). It can also regulate the group at a "collective level" by sending a global notification encouraging the group to divide tasks more evenly. Regulation by learners can occur when one learner encourages another to collaborate more or when a learner regulates their own collaboration.

Finally, a teacher can regulate collaboration by advising learners directly on task sharing or participation.

Finally, an "Other collaboration tool" criterion allows for the mention of any additional tool that fosters collaboration in the lab and is not included among the previously listed ones.

Table 3 summarizes the analysis criteria of the "Collaboration" category we chose to include in our analysis.

## Evaluation of collaboration and learning

We established analysis criteria to analyse the presence and type of evaluations of collaboration and learning quality in VRLs. The "Purpose of the evaluation" criterion is filled if a study evaluating the VRL is included in the analysed paper. This analysis criterion describes what was evaluated, such as commitment, collaboration, or learning.

For each paper analysed, if collaboration was evaluated within the VRL, we further investigated how collaboration between users was evaluated and measured. The following criteria are filled if the "Purpose of the evaluation" criterion concerns collaboration, i.e., if an article evaluates the lab and includes an evaluation of collaboration. The "Data collected to measure collaboration" criteria specifies whether the data collected during the study is qualitative ("qualitative"), quantitative ("quantitative"), both qualitative and quantitative ("both"), or if no data was collected ("none"). For example, an evaluation of collaboration using a questionnaire with open-ended questions would collect qualitative data, while an evaluation of collaboration based on the number of messages sent by each learner in a text chat would collect quantitative data. The "Type of indicator" criterion further specifies the type of indicator used to measure the quality of collaboration. This is a no preset value, as there are a large number of possible indicators for assessing collaboration. An indicator could, for example, be a questionnaire, a grade, time spent in the VRL by each person or messages in a text chat. The "Results" criterion describes the results obtained when evaluating collaboration within the VRL. For example, a study might conclude that students were significantly more engaged in lab activities when the text chat was enabled. The "Study duration" and "Number of participants" criteria specify the duration of the study and the number of participants involved. Finally, the "Level of education" criterion specifies the education level of the students involved in the evaluation ("Primary school", "Secondary", "Higher", "Other").

To examine the impact of collaborative VRLs on learning, we introduced the "Learning measure" criterion. This criterion applies when a publication reports a study that includes an evaluation of learning within the VRL. It is designed to be open-ended, allowing coders to specify the type of analysis or assessment method used. Additionally, the "Impact of the VRL on learning" criterion is used to categorize the reported effect as "Positive," "Negative," "Neutral," or "Unknown."

Table 4 summarizes the analysis criteria of the "Evaluation of collaboration and learning" category.

## Results

This section summarizes the results obtained for each category of analysis criteria. It is organized into sub-sections corresponding to each analysis category. Detailed tables showing the coding scheme for each paper, along with their identification number are available in Appendix A, Appendix B and Appendix C.

**Table 3** Collaboration category

Analysis criterion	Possible criterion values
Group size	"Limited"; "Unlimited"
Collaboration between learners	"Yes"; "No"
Collaboration between learners and teachers	"Yes"; "No"
Distinct roles between students	"Yes"; "No"
Role assignment	"By the system"; "By the learner"; "By the teacher"; "Several possibilities"; "No role"; "Unknown"
Task requiring several users	"Yes"; "No"
Communication	"Synchronous"; "Asynchronous"; "Both"; "Unkown"; "None"
Type of communication	"Audio"; "Text chat"; "Video"; "Other"; "Multiple artifacts"; "No type of communication"
Guidance	"Yes"; "No"
Type of guidance	"Action blocking"; "Script"; "Manual guidance by the teacher"; "Manual guidance by the student"; "Other"; "No type of guidance"
Group awareness	"Peer activities"; "Group performance"; "Individual performance"; "Teacher presence"; "Peer presence"; "Several artifacts"; "Other"; "None"
Type of tool of group awareness	No preset value
Regulation of collaboration	"Regulated at the individual level"; "Regulated on a collective level"; "Regulated by the learners"; "Regulated by the teachers"; "Other"; "No regulation"
Type of regulation	No preset value
Other collaboration tool	No preset value

## System

Appendix A provides an overview of the disciplines involved in the analysed papers, revealing a predominant focus on STEM (Science, Technology, Engineering, and Math), with fields like electronics, computer science, chemistry, and mechanical engineering being particularly well represented.

According to Fig. 3a, publications mostly concern virtual labs (n = 28, 45%), although the distribution between remote and virtual laboratories is fairly even.

Figure 3billustrates the relative distributions of user location, showing that users are often non co-located (n = 29, 47%) or that both location types are represented (n = 26, 42%). This results confirms the value of VRLs for manipulating resources from different locations.

With regard to temporality, Figure 3cshows that synchronous connections are predominant, with users having the possibility to connect and engage in real-time actions in the majority of cases (n = 56, 90%).

Most of the time, the laboratory's lifetime information is unspecified according to Fig. 3d(n = 35, 57%). Results also show that the laboratories studied are usually 2D (n = 27, 44%, see Fig. 3e). Finally, interaction traces are stored in about one-third of cases (n = 22, 35%, see Fig. 3f). Appendix A further detail the diversity of stored interaction traces, which include metrics like scores and successes, time data, resource access logs, recordings, as well as mouse and keyboard activity traces.

**Table 4** Evaluation of collaboration and learning category

Analysis criterion	Possible analysis criterion values
Purpose of the evaluation	No preset value
Data collected to measure collaboration	"Qualitative"; "Quantitative"; "Both"; "None"
Type of indicator	No preset value
Results	No preset value
Study duration	No preset value
Number of participants	No preset value
Level of education	"Primary school"; "Secondary"; "Higher"; "Other"
Learning measures	No preset value
Impact of the VRL on learning	"Positive"; "Negative"; "Neutral"; "Unknown"

## Collaboration

This section describes results about collaboration among users in the analysed papers. Figure 4 shows group sizes in the analysed labs and the proportion of tasks requiring several users. According to Fig. 4a, the distributions between limited ( $n = 24$ , 39%) and unlimited ( $n = 21$ , 34%) size groups are close. The majority of the labs ( $n = 34$ , 55%, see Fig. 4) do not include tasks that require several users (see Fig. 4b).

Figure 5 illustrates the proportion of publications in which the laboratory offers opportunities for collaboration between learners, and between learners and teachers. Figure 5a shows that collaboration between learners is highly prevalent ( $n = 53$ , 85%). One laboratory does not involve collaboration between students (Alghamdi et al., 2024), but this can be explained by the fact that it is dedicated to collaboration between students and teachers. Collaboration between learners and teachers, although slightly less common, still appears in 57% of the VRLs ( $n = 35$ ), as depicted in Fig. 5b.

Figure 6 illustrates the proportion of VRLs in which distinct roles are assigned to students and the mechanisms of role assignment. Figure 6a shows that students have distinct roles in the labs in 29% of cases ( $n = 18$ ). These roles are most commonly assigned by the learners themselves (10%,  $n = 6$ ), though assignment by the system (1%,  $n = 1$ ), by the teacher (3%,  $n = 2$ ), or via multiple assignment possibilities (5%,  $n = 3$ ) are also observed. However, in 81% of the publications ( $n = 50$ ), role assignment is not specified, either because distinct roles were not defined, or because this information was not provided.

Communication modalities in VRL environments, as presented in Table 5, reveal that synchronous communication is the most frequent ( $n = 33$ ), followed by VRLs that support both synchronous and asynchronous modes ( $n = 15$ ). Asynchronous communication alone is present in only 2 publications, while 7 publications lack detail on communication modalities, and 5 publications do not provide any communication tools at all. Figure 7 further details the types of communication used, showing that most systems support communication through multiple artifacts ( $n = 34$ ), though audio-only ( $n = 4$ ), text chat-only ( $n = 7$ ), and other communication types ( $n = 3$ ) are also represented. For example, the *CCLI Project*, a computer networked virtual laboratory project, features text chat as a communication tool (Dong & Guo, 2011). The virtual chemistry laboratory *LeARn*, for its part, enables voice communication between its users in the virtual environment (Ahmed et al., 2021). The integration of these communication tools has the advantage of facilitating discussions and explanations between students, and thus building knowledge (Dillenbourg, 1999).

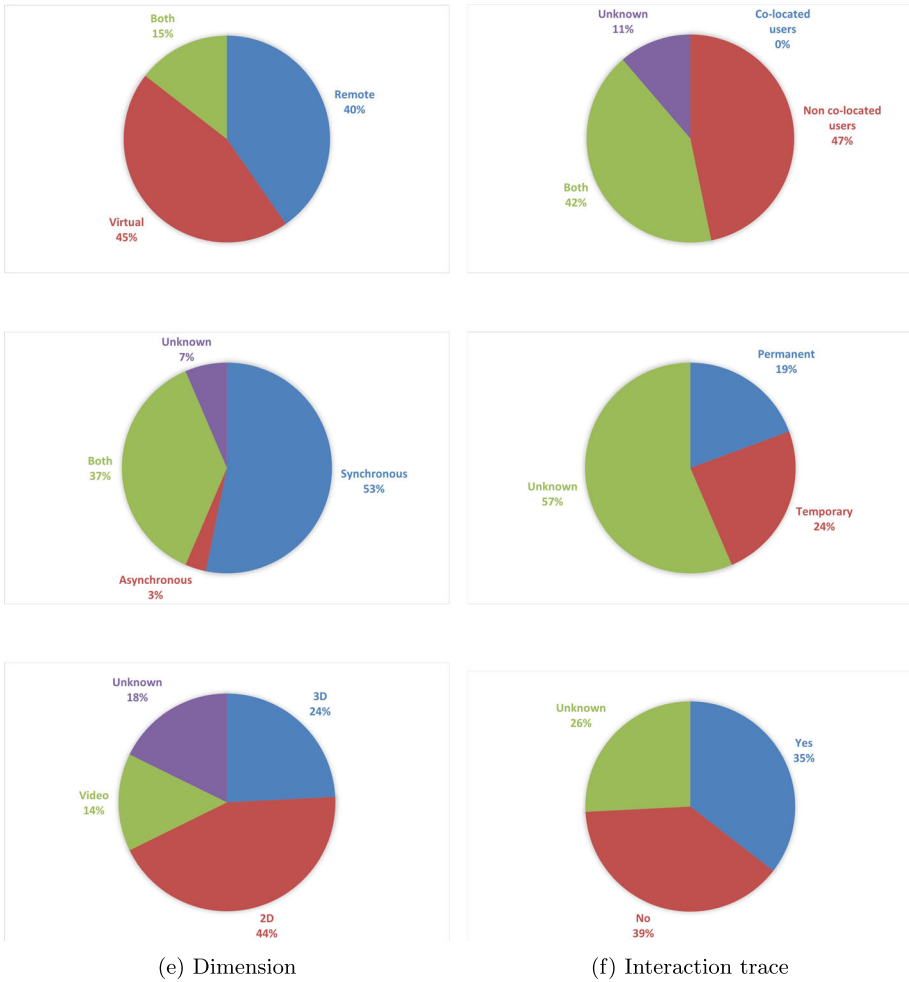


Fig. 3 Results of the System category

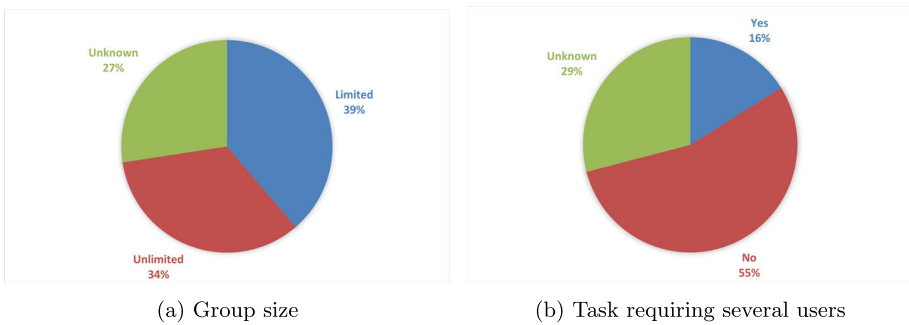
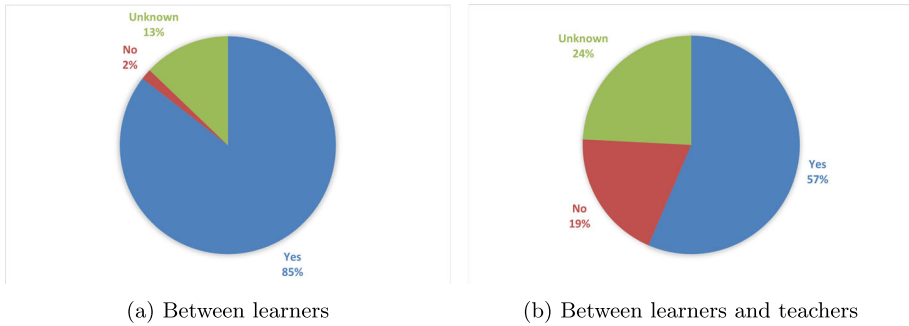


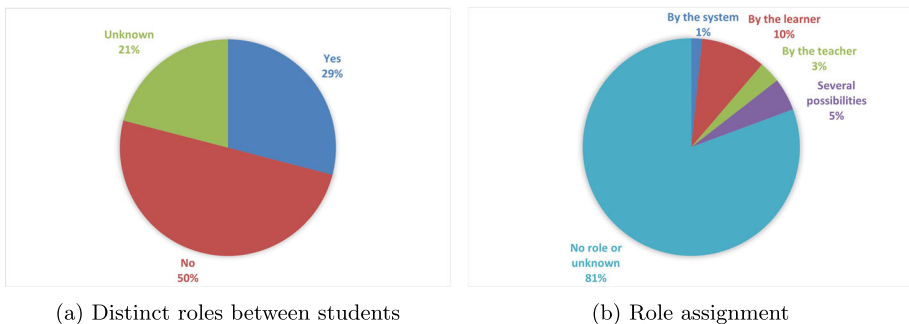
Fig. 4 Group sizes in laboratories and proportion of tasks requiring several users



**Fig. 5** Collaboration between learners and between learners and teachers

Another important aspect of collaboration that has been analysed is guidance. As a reminder, in this paper, guidance is defined as tools that support the establishment of mental collaboration scripts by providing instructions or suggesting actions. According to Table 6, guidance tools are relatively uncommon, with only 13 VRLs incorporating them. When collaboration is guided, this can take the form of action blocking, collaborative script, or manual guidance from teachers. For example, Arora et al. (2017) scripts collaboration between students by proposing a division of tasks among students within the project in *TMED-COG*. The teacher can use a dedicated module to assign a structured division of labor within a project (Arora et al., 2017). Figure 8 presents an example from the *TMED-COG* system, where four students are each assigned distinct programming tasks necessary for completing the group project. However, the structure of collaborative guidance varies significantly by discipline. For instance, the task allocation in *TMED-COG*'s computer science environment contrasts sharply with that of Farah et al. (2015)'s electronics lab, where students must jointly operate the same instruments remotely. This variability significantly influences how guidance tools can be effectively implemented. It should also be noted that some laboratories incorporate task-oriented guidance but it is more oriented towards task completion without explicitly targeting collaboration. For example, e-Labs features guidance via milestones imposed on students (Bardeen & Wayne, 2016). However, it is not explicitly stated whether this guidance concerns only the task or also collaboration on the task.

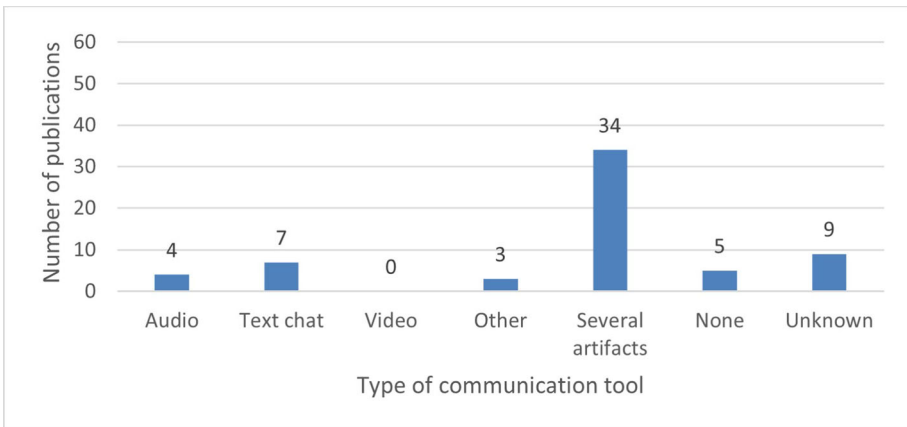
Subsequently, we analysed VRL with regard to group awareness functionalities (see Fig. 9). Figure 10 illustrates the types of information provided by group awareness tools in the laboratories studied. Specifically, peer presence is visible in 10 laboratories, peer activities are visible in 9 laboratories, and 20 laboratories integrate multiple artifacts for group



**Fig. 6** Roles in laboratories

**Table 5** Communication tools covered in the reviewed publications

Communication	Number of publications	References (ID nr. from Appendix A)
Synchronous	33	1, 2, 3, 9, 10, 11, 13, 15, 16, 17, 20, 21, 23, 24, 25, 29, 30, 32, 34, 38, 40, 41, 42, 43, 45, 46, 48, 49, 51, 52, 54, 58, 59
Asynchronous	2	31, 62
Both	15	8, 14, 18, 19, 22, 26, 27, 28, 37, 39, 53, 56, 57, 60, 61
Unknown	7	4, 5, 6, 12, 33, 44, 47
No communication	5	7, 35, 36, 50, 55



**Fig. 7** Types of communication tool in laboratories

awareness. For example, the online electronics lab *Circuit Warz* supports group awareness through scoreboards, allowing the performance of group members to be visualised in real time (Callaghan et al., 2013) (see Fig. 9). The virtual computer laboratory *eGuru* has a group awareness tool in the form of coloured circles to visualise the presence of peers (Arora et al., 2022). The implementation of these presence and performance awareness tools, by providing information about the group, is expected to improve its effectiveness (Kirschner et al., 2018) and co-construction of knowledge (Chen et al., 2018). Notably, teacher presence, group performance, and individual performance indicators, are never implemented as stand-alone tools, they are always present with other awareness tools. This can be explained by the need to complement this information with additional data; for instance, group performance holds limited value if we lack insight into the individual actions taken to achieve or enhance that performance. In addition, we did not identify any group awareness tools in 22 VRLs. Seven of these don't incorporate group awareness tools, while 15 publications do not indicate whether these tools are present.

According to Table 7, tools enhancing regulation for collaboration are very rare in VRLs. Indeed a total of 8 laboratories have been identified as containing such tools. Among these, 3 VRLs include tools that facilitates regulation by learners, while the remaining 5 VRLs

**TMED:Monitor Live View**

Project Name: **SnakesAndLadders**      Team Name: **TeamCQP**

Suman working on initializeBoard.java

```

1: package gameBoard;
2: public class initializeBoard
3: {
4:
5: }
```

Jimmi working on Snakes.java

```

1: package gameBoard;
2: public class Snake {
3:     int startPosition;
4:     int endPosition;
5:     int colorElement;
6:     Snake(int start, int end, int color)
7:     {
8:         startPosition= start;
9:         endPosition= end;
10:        colorElement= color;
11:    }
12: }
```

Zubair working on Snakes.java

```

1: package gameBoard;
2: public class Snake {
3:     int startPosition;
4:     int endPosition;
5:     int colorElement;
6:     Snake(int start, int end, int color)
7:     {
8:         startPosition= start;
9:         endPosition= end;
10:        colorElement= color;
11:    }
12: }
```

Gopi working on Ladder.java

```

1: package gameBoard;
2: public class Ladder {
3:     int startPosition;
4:     int endPosition;
5:     int colorElement;
6:     Ladder(int start, int end, int color)
7:     {
8:         startPosition= start;
9:         endPosition= end;
10:        colorElement= color;
11:    }
12: }
```

**Fig. 8** View of the team showing the division of tasks in *TMED-COG* (Arora et al., 2017)

**Table 6** Guidance tools covered in the reviewed publications

Guidance	Sub-category	Number of publications	References (ID nr. from Appendix A)
Yes	Script Blocking By the teacher Other Unknown	4 3 4 2 1	6, 19, 38, 54 24, 34, 43 9, 18, 30, 48 37, 39 1
No		40	2, 3, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 20, 21, 22, 23, 25, 26, 27, 28, 29, 31, 32, 35, 36, 41, 42, 44, 45, 46, 49, 50, 52, 53, 55, 57, 59, 60, 61, 62
Unknown		8	3, 5, 33, 40, 47, 51, 56, 58

support regulation by teachers. Regarding this last option, in *TMED-COG*, teachers can regulate collaboration by messaging students directly (Arora et al., 2017). In *Lab@Home*, teachers act as regulators by distributing tasks among students (Saliah-Hassane et al., 2011). This approach is consistent with findings from (Chen et al., 2018), who argue that teacher feedback enhances idea generation, knowledge development, and student motivation. In the remote lab developed by De La Torre et al. (2013), a designated “director” controls which user may interact with the system at any given time, creating a unique form of turn-based collaboration regulation. While this method may be effective in fields like control engineering that require shared use of resources, it is less suitable for scenarios such as in *TMED-COG*’s computer science environment, where each student works independently and

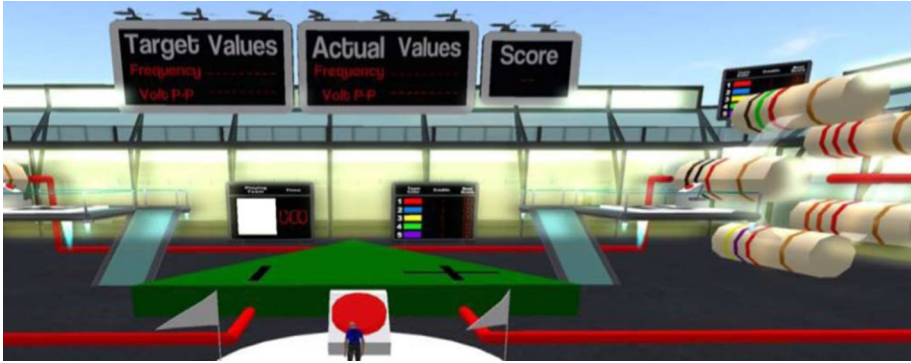


Fig. 9 Group awareness through scoreboards in *Circuit Warz* (Callaghan et al., 2013)

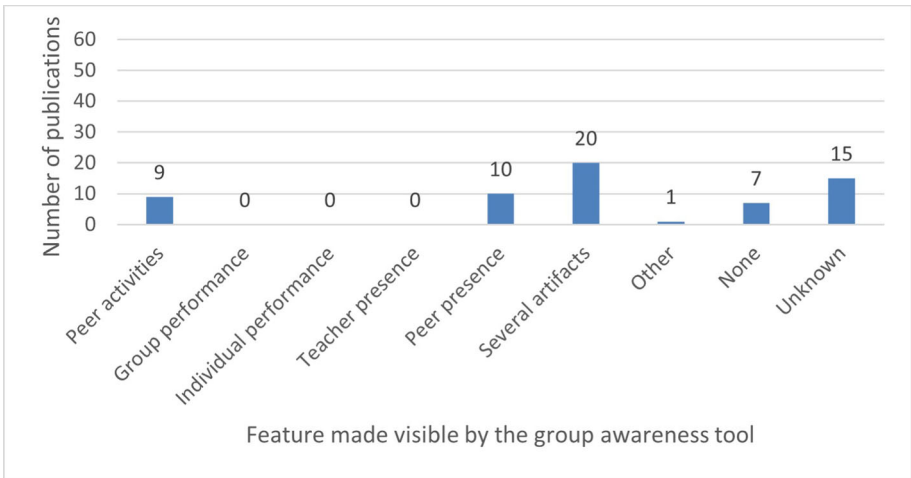


Fig. 10 Types of information provided by group awareness tools in laboratories

concurrently (Arora et al., 2017). As with guidance mechanisms, the design of regulatory tools must be tailored to the specific needs and practices of the discipline.

Finally, we note the presence of additional collaborative tools in some VRLs, as detailed in Appendix B. These tools may include note-taking applications, for example. In addition, some VRLs are integrated with other platforms such as Gitlab, Teams, Moodle, Adobe Connect, or Zoom. These platforms may provide additional features for collaboration.

### Evaluation of collaboration and learning

To address RQ3, we analysed the evaluation of collaboration and learning in educational VRLs. The results are shown in Appendix C.

Figure 11 shows the types of studies among all publications and the types of data collected in studies focused on collaboration. It has to be noted that 31% of publications (n = 19) included a study to evaluate collaboration among users (see Fig. 11a) and among these studies, 53% (n = 10) relied exclusively on qualitative data, while 37% (n = 7) used only quantitative data. A smaller subset of studies, 10% (n = 2), adopted mixed-methods approach and used

both qualitative and quantitative data (see Fig. 11b). Additionally, 48% of publications ( $n = 30$ ) included evaluation studies, though these were unrelated to collaboration (see Fig. 11a). Finally, 21% of publications ( $n = 13$ ) did not incorporate any evaluation at all (see Fig. 11a).

The evaluation of collaboration employs a variety of indicators, as detailed in Appendix C. Questionnaire data emerges as a frequent metric, while behavioral data, such as learning outcomes are analysed in some cases, as demonstrated in Dutton (2023). Additionally, Du et al. (2023) collected physiological data, measuring the mental load induced by collaboratively problem-solving through an EEG system. It should be noted, however, that physiological measures such as EEG do not assess collaboration quality but rather provide insight into cognitive load during collaborative task. Finally, all the studies that include collaborative data analysis and provide information on the educational level of students, involve higher education students (see Appendix C).

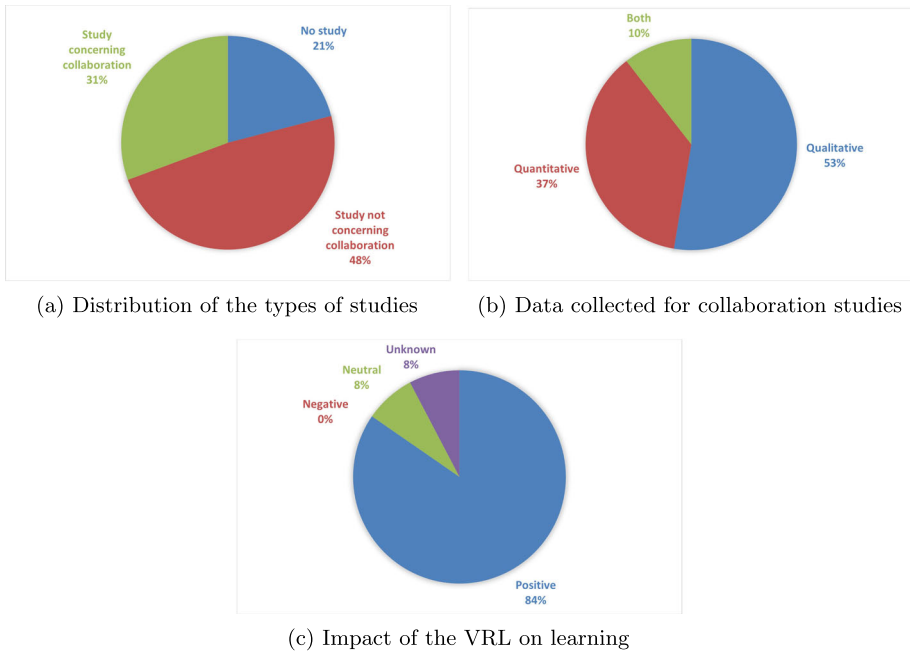
To address RQ3, we also analysed the evaluation of learning in educational VRLs. As shown in Appendix C, of the 62 laboratories examined, 26 studies focused on determining the effect of the collaborative VRL on learning, which is more than the number of studies on collaboration. The indicators used to measure learning are diverse, including questionnaires, feedback, tests, grades and task completion metrics within the VRL, as detailed in Appendix C. These indicators are either self-reported or based on performance during the task.

Figure 11c shows the impact of the VRL on learning for all laboratories that included a study on learning outcomes. Among these laboratories, 84% ( $n = 22$ ) have a positive impact on learning (see Fig. 11c). The preponderance of favorable outcomes indicates a positive impact on student learning outcomes attributed to collaborative online laboratories.

Finally, it should be noted that the study of collaboration and learning can be combined in a publication. A notable illustration of this is found in Teng et al. (2024)'s analysis, where the grades on the tasks performed in the laboratory are compared across different collaborative modalities. Teng et al. (2024) concludes that students who first collaborate and then complete an activity individually in the VRL are more successful than students who complete an individual task first and then collaborate. Learning outcomes are also analysed to evaluate the impact of collaboration on student success in the VRL of Dutton (2023).

**Table 7** Regulation tools covered in the reviewed publications

Regulation of collaboration	Sub-category	Number of publications	References (ID nr. from Appendix A)
Yes	By teachers By learners	5 3	6, 9, 38, 45, 57 17, 59, 60
No		39	2, 4, 7, 10, 11, 12, 13, 14, 15, 16, 19, 20, 21, 22, 25, 26, 28, 29, 30, 31, 32, 34, 35, 36, 39, 41, 42, 43, 44, 46, 48, 49, 50, 52, 53, 54, 55, 58, 62
Unknown		15	1, 3, 5, 8, 18, 23, 24, 27, 33, 37, 40, 47, 51, 56, 61



**Fig. 11** Distribution of the types of studies among all publications (a), type of data collected among studies concerning collaboration (b) and impact of the VRL on learning according to studies which evaluate learning (c)

## Discussion

The integration of CSCL findings into educational VRLs represents a promising avenue of inquiry. To investigate this integration, we conducted a systematic literature review examining how past and present educational VRLs support collaboration.

### **RQ1: What are the learning areas and main properties of VRLs designed to support collaboration?**

The investigation began with an examination of the main characteristics of collaborative VRLs. We found that the majority of publications focus on VRLs in the field of science, technology, engineering, and mathematics (STEM). This can be explained by the fact that these areas inevitably require the acquisition of skills through laboratory exercises. It is also conceivable that this over-representation of STEM subjects reflects a lack of interest among researchers from other disciplines in the design of VRLs within their respective fields. However, this prevalence of STEM subjects may also be perceived as a limitation of our study, as the under-representation of other disciplines may be attributed to our selection of terms and analysis criteria. For instance, in other fields such as health, the term "simulation" is used rather than "virtual laboratory" (Bracq et al., 2019). This can explain why STEM-related disciplines stand out in this study. However, while the majority of the disciplines were in the STEM field, it is important to note that the latter encompassed subjects as diverse as computer science, electronics and biology. These differences in terms of discipline have an impact on the learning objectives and the implementation of task support tools, in particular tools for guiding and regulating collaboration when the latter are task-oriented. Furthermore,

none of the reviewed laboratories were fully co-located. This confirms the need for tools that encourage remote collaboration. Most VRLs are synchronous, two-dimensional, and often omit details on their operational lifetime. The prevalence of 2D labs is consistent with the findings from Roda-Segarra (2021), which indicated that only 1 virtual laboratory incorporated immersive technologies. We could explain this observed preference by the fact that 3D environments require high-performance computers, or by the fact that 3D is more often linked to terms like “simulation” or “immersive” than with “laboratory”. In some instances, VRLs incorporate user interaction traces. Such traces can be employed for the analysis of behaviors, including the quality of collaborative learning between users.

## **RQ2: What tools and features are integrated into VRLs to facilitate and enhance collaboration among users?**

We then focused on the affordances supporting collaborative skills within VRLs. It is noteworthy that the great majority of laboratories allowed for collaboration between students, whereas student-teacher collaboration was less supported. This can be explained by the fact that integrating collaboration into a group of students has pedagogical benefits in terms of developing teamwork skills and building knowledge among members (Duit & Treagust, 1998), whereas collaboration with the teacher is more based on an occasional support role. An area for improvement for VRLs designers could therefore be to explore the pedagogical benefits of student-teacher collaboration more deeply. Regarding collaboration tools, synchronous and mixed synchronous/asynchronous communication tools are prevalent, which is consistent with the observation that the studied laboratories are predominantly designed for use in a synchronous manner. Furthermore, it can be inferred from this outcome that communication, an important aspect of collaboration, is due consideration in the laboratories. Group awareness tools, which help students track peers’ presence and activities through online members lists, video calls and shared workspaces, are also well-represented (see Appendix B). This type of tool is very present in online collaborative platforms in general, which may explain their predominance in the studied VRLs. The successful integration of communication and group awareness tools in VRLs is promising, as it helps to establish and maintain common ground, a foundational component of effective remote collaboration (Olson & Olson, 2000). Facilitating shared understanding and mutual awareness among participants is essential to fostering productive collaboration and learning. However, we noted that performance awareness tools are less common (see Appendix B), and could be beneficial in future VRLs. We also observed a lack of functionalities designed to guide collaboration. Most VRLs simply give students the task statements and leave them to work on their own without further instructions. Collaboration instructions may be given by the teacher, such as on the distribution of the tasks among students, but the VRLs rarely include mechanisms to facilitate or automate this process. This lack of structured guidance tools could limit the effectiveness of collaborative learning within these platforms, as students may struggle to achieve optimal coordination and engagement on their own. Implementing automated guidance features, such as role assignment or task distribution support, could enhance collaborative processes, ensuring that students can engage in more organized and meaningful joint activities. Additionally, very few VRLs incorporate tools for regulating collaboration. We can explain this by the fact that the VRLs studied are aimed at expert students (third year and above) and not novice first-year students. Future research should further examine the integration of collaboration guidance and regulation tools in VRLs. These features are likely to enhance students’ ability to coordinate effectively and achieve learning objectives. However, their implementation should always be considered in light of the specific disciplinary context, as task types and

collaboration structures may vary considerably. This diversity in task demands could partly explain the limited deployment of such tools in some VRLs.

### **RQ3: What methods are used to evaluate the quality of collaboration and learning in VRLs?**

It has been observed that one-third of the papers included a study to assess the quality of collaboration. In addition, just over one-third of the publications mention the impact of VRL on student learning. These studies exclusively involved higher education students. This observation is encouraging in that it suggests a willingness to assess collaboration and learning within laboratories, which is an important indicator of the effectiveness of integrated collaborative tools. However this result is not entirely satisfying as many papers did not include assessments of collaboration or learning. This outcome aligns with the observation of Birkeland et al. (2023) regarding the dearth of research on learning analytics for collaborative VRLs. Thus, it may be worth expanding this aspect to improve our understanding of VRLs effectiveness. We also noted that qualitative data, mostly collected through questionnaire, is predominant for evaluating collaboration. We can explain the predominance of questionnaires by their simplicity despite collecting only subjective data. Furthermore, there are very few studies that integrate physiological data for assessing collaboration, potentially due to the logistical complexity of obtaining such data. Nevertheless, integrating physiological data, particularly neural data, into the field of Technology-Enhanced Learning (TEL) is a promising avenue of research, whether for the purpose of improving teaching tools or for gaining a deeper understanding of neurocognitive processes (Howard-Jones et al., 2014). Evaluation of learning in VRLs often relies on self-report questionnaires and performance-based assessments such as tests or analysis of in-system activities. Our review reveals a predominantly positive effect of collaborative VRLs on student learning—an outcome that supports the conclusions of Chen et al. (2018), whose meta-analysis demonstrated greater knowledge gains in CSCL settings compared to individual computer-supported learning. Thus, collaboration in VRLs represents a critical factor in improving learning outcomes and warrants further attention in both research and measurement.

### **Implications and recommendations for future research**

The present review identified both strengths and limitations in current VRL implementations. To address these issues, we recommend that future research explicitly incorporate tools for guiding and regulating collaboration—provided these features align with the needs of the relevant discipline. Such tools have the potential to improve the collaborative process and, in turn, enhance learning outcomes. This argument is consistent with the theoretical underpinnings of distributed cognition (Hutchins, 2000), social constructivism (Leinonen et al., 2000), and Vygotsky's socio-cultural theory (Vygotsky, 1978). Lastly, given the predominantly quantitative nature of our review, we suggest a greater focus on qualitative research to explore overlooked aspects in greater depth.

### **Limitations**

It bears noting that our study is not without limitations. First, our selection of analysis criteria is not exhaustive and could have included several other aspects of collaborative learning. For

example, Jeong and Hmelo-Silver (2016) included other affordances that foster collaboration such as "Establishing a joint task", "Sharing resources", "Engaging in co-construction" and "Finding and building groups and communities". Future research might explore these aspects in VRLs, investigating the task types, the strategies employed to share resources, the tools utilized to establish and maintain a common ground, and the methods used to form groups. While this approach may have resulted in a less comprehensive analysis of collaboration, we decided to focus our investigation on the analysis criteria that we deemed most pertinent to the research questions. Another limitation concerns our inclusion and exclusion criteria. For example excluding non-English publications may have reduced the number of studied VRLs. Additionally, excluding articles not talking about education is also restrictive and has eliminated a great deal of papers talking about collaborative laboratories. However it was also important to keep this criterion since our study is about educational laboratories.

## Conclusion

The integration of a collaborative dimension within VRLs is identified as a crucial strategy for engaging learners in the process of learning. This systematic literature review analysed published research on educational VRLs between 2011 and 2025, highlighting in particular their contribution in terms of providing tools that foster collaboration between learners and between learners and teachers. To ensure that the collection of articles was conducted in a rigorous manner, we followed the PRISMA methodology, resulting a final set of 62 papers that were selected and analysed. To guide our analysis, we established specific criteria classifying them into distinct categories. The "System" category provided a detailed technical description of each laboratory and addressed RQ1. The "Collaboration" category addressed RQ2 by examining the ways in which users collaborate in these VRLs, as well as the presence of tools designed to facilitate such collaboration. Based on a review of relevant collaboration theories, we identified analysis criteria such as the presence of communication tools, group awareness tools, guidance tools and regulation tools. Finally, the "Evaluation of collaboration and learning" category enabled us to examine the studies that assess the quality of collaboration and learning within VRLs and therefore to answer RQ3.

We observed that laboratories often incorporate communication tools and group awareness tools which support interaction and awareness of peer activity. However, functionalities aimed at guiding and regulating collaboration are notably underrepresented. Additionally, studies that evaluate collaboration quality are present in only about one-third of the laboratories studied, whereas the impact of the VRL on learning is evaluated in more than one-third of the publications. These findings allowed us to identify both the strengths and weaknesses of collaboration in VRLs, pointing to areas for future improvement. We recommend that future research into VRLs design include robust tools for collaboration guidance and regulation and that their impact be evaluated in dedicated studies.

It should be noted that the review has limitations. For example, the analysis criteria are not exhaustive. Future work could incorporate new analysis criteria, such as the way in which resources are shared in educational VRLs. Finally, only educational laboratories were included, as the focus was on this particular laboratory use case.

### A. Coding scheme of the reviewed publications for System category

Nr.	Reference	Name	Discipline	Laboratory type	Location	Temporality	Lifetime	Dimension	Interaction trace
1	Ahmed and Lataifeh (2024)	LeARn	Chemistry	Virtual	Non co-located users	Synchronous	Temporary	3D	0
2	Ahmed et al. (2021)	LeARn	Chemistry	Virtual	Non co-located users	Synchronous	Permanent	3D	No
3	Alghamdi et al. (2024)	TU-Virtual	Computer science	Virtual	Both	Synchronous	Permanent	2D	No
4	Alsaleh et al. (2022)	Relmagine	STEM	Both	Both	Synchronous	Unknown	3D	No
5	Al-Zoubi et al. (2023)	0	Physics	Remote	0	0	0	0	0
6	Arora et al. (2017)	TMED-COG	Computer science	Virtual	Non co-located users	Both	Permanent	2D	Yes (Activities)
7	Arora et al. (2022)	eGuru	Computer science	Virtual	Non co-located users	Both	Permanent	2D	Yes (Gitlab)
8	Bardeen and Wayne (2016)	0	Nuclear physics	Both	Both	0	0	2D	Yes
9	Bochicchio et al. (2015b)	WeCollab	Several	Remote	Non co-located users	Synchronous	Unknown	Video	No
10	Bochicchio et al. (2015a)	EDOC	Sciences	Remote	Non co-located users	Both	Permanent	Video	0
11	Bochicchio et al. (2016)	BIOforIU research project	Biology	Remote	Both	Synchronous	Unknown	Video	Yes (Mouse, keyboard)
12	Bogdanov et al. (2012)	0	Automatic control	Remote	Both	Synchronous	Unknown	Video	0
13	Callaghan et al. (2013)	Circuit Wartz	Electronics	Both	Non co-located users	Synchronous	Unknown	3D	Yes (Completion time, quiz, score)
14	Carreón et al. (2018)	0	Networks	Remote	Non co-located users	Both	Unknown	2D	No
15	Chancharoen and Phanomchoeng (2022)	Telepresence Laboratory	Mechanical engineering	Remote	Non co-located users	Synchronous	Unknown	Video	No

16	Chang et al. (2011)	0	Mechanical engineering	Virtual	Non co-located users	Synchronous	0	3D	0
17	Cibuljska et al. (2024)	AVRES	STEM	Virtual	Both	Synchronous	Unknown	3D	No
18	Ciolacu et al. (2021)	E4LDIU	Optics	Remote	Non co-located users	Synchronous	Temporary	0	No
19	Coelho et al. (2024)	4.0 laboratories	Engineering	Virtual	Non co-located users	Both	Unknown	0	Yes (Activities and progress)
20	Corbi et al. (2019)	0	Programming	Virtual	Both	Asynchronous	Permanent	2D	Yes (Tools used in VRL)
21	Desai et al. (2017)	MMCVL	Chemistry	Virtual	Both	Synchronous	Temporary	3D	Yes
22	Dong and Guo (2011)	CCLI Project	Networks	Virtual	Both	Both	Temporary	2D	0
23	Douar et al. (2023)	3DVL@ES	Sciences	Virtual	Both	Synchronous	Unknown	3D	No
24	Du et al. (2023)	0	Computer networks	Virtual	Both	0	0	0	0
25	Dutton (2023)	HHMI	Biology	Virtual	Non co-located users	Synchronous	Unknown	2D	No
26	Drysdale and Braithwaite (2017)	0	STEM	Remote	Non co-located users	Synchronous	Temporary	2D	Yes
27	Estriégana et al. (2021)	0	Computer Technology	Virtual	Both	Both	0	2D	Yes (Success and failure)
28	Fabini et al. (2021)	SecTULab	Cyber security	Both	Non co-located users	Both	Temporary	2D	No
29	Farah et al. (2015)	LAB-EN-VI	Network Architectures	Remote	Non co-located users	Both	Unknown	2D	No
30	Farah et al. (2016)	INT-RE-LAB	Electronics	Remote	Non co-located users	Both	Unknown	2D	No
31	Gleich et al. (2020)	CORELA	Electrical engineering	Remote	Both	Both	Unknown	2D	No
32	González Rodrigo et al. (2014)	Virtual Lab of Continuum Mechanics	Mechanics of Media	Virtual	Both	Both	Unknown	3D	Yes (Rooms visited, resources downloaded, virtual whiteboards)





**B. Coding scheme of the reviewed publications for Collaboration category**

Nr.	Group size	Collab. btw. learners	Collab. btw. learners and teachers	Dist. roles btw. students	Role assignment	Task requiring several users	Guid. type of guid.	Group aware. and type of group aware.	Regul. of collab.	Com. and type of com.	Other collaboration tool
1	Lim.	Yes	0	0	0	No	Yes	0	0	Sync. Sync.	0
2	Unlim.	Yes	Yes	No	No role	No	No	Sev. art. (Peer activities, peer presence and teacher presence)	No regul.	Sync. (Audio)	0
3	Lim.	No	Yes	Yes	Unkn.	No	0	0	0	Sync. (Text chat)	Screen sharing
4	Unlim.	Yes	0	No	No role	No	No	Peer presence	No regul.	Unkn.	0
5	0	0	0	0	0	0	0	Peer activities	0	0	0
6	Lim.	Yes	Yes	Yes	By the learner	No	Yes (Script)	(Eclipse IDE awareness widgets)	Regul. by teachers (messages)	0	0
7	Unlim.	Yes	Yes	No	No role	Yes	No	Peer presence (Dashboard colored circle)	No regul.	No	Gitlab forms for asking (learners) and answering (teachers) questions

8	Lim.	Yes	Yes	0	0	Yes	No	0	0	Both (Sev. art.)	Note-taking facilities
9	0	Yes	Yes	Yes	No role	Yes	Yes (Manual by the teacher)	Sev. art. (Connected people, completed tasks)	Regul. by teachers (Instructions)	Sync. (Sev. art.)	Note-taking facilities, whiteboard
10	0	Yes	Yes	No	No role	0	No	Sev. art.	No regul.	Sync. (Sev. art.)	Note-taking facilities
11	Unlim.	Yes	Yes	0	0	No	No	Peer presence (Video conferencing)	No regul.	Sync. (Sev. art.)	Note-taking facilities
12	Lim.	Yes	Yes	No	No role	No	No	No	No regul.	Unkn.	0
13	0	Yes	No	No	No role	No	No	Sev. art. (Actions and presence of peers, group performance via score display)	No regul.	Sync. (Other)	Comparing scores and speed with other teams
14	Unlim.	Yes	Yes	Yes	By the system	0	No	Peer presence (Google+ API)	No regul.	Both (Sev. art.)	0
15	Unlim.	Yes	Yes	No	No role	No	No	Peer presence (Zoom)	No regul.	Sync. (Sev. art.)	Note-taking facilities

16	Lim.	Yes	0	0	0	By the learner	0	No	Peer activities	No regul.	Sync. (Text chat)	0
17	Unlim.	Yes	No	No	No	No role	No	No	Peer presence (Peer avatars)	Regul. by learners (Verbal exchanges)	Sync. (Audio)	Multiplayer functionalities offered by "Photon Engine" (Unity) Teams, Moodle (Note-taking facilities) Microsoft Planner, Microsoft Teams Adobe Connect, note-taking facilities
18	0	0	0	0	0	0	0	Yes (Manual guid. by the teacher)	0	0	Both (Sev. art.)	Both (Sev. art.)
19	Lim.	Yes	Yes	No	No	No role	No	Yes (Script)	Peer activities	No regul.	Both (Sev. art.)	Both (Sev. art.)
20	Unlim.	Yes	Yes	No	No	No role	No	No	Sev. art. (Adobe Connect + Jupyter-Notebook)	No regul.	Sync. (Sev. art.)	Sync. (Sev. art.)
21	Lim.	0	Yes	0	Unkn.	Unkn.	Yes	No	Peer act.	No regul.	Sync. (Audio)	0
22	Lim.	Yes	No	No	Unkn.	Unkn.	0	No	No	No regul.	Both (Text chat)	Google Chat Document sharing, note-taking facilities
23	0	Yes	No	No	0	0	Yes	No	0	0	Sync. (Sev. art.)	Sync. (Sev. art.)
24	Lim.	Yes	No	Yes	Unkn.	Unkn.	Yes	Yes (Act. block.)	0	0	Sync. (Sev. art.)	Sync. (Sev. art.)

25	Unlim.	Yes	Yes	No	No	No	No	No	Peer pres- ence (Zoom)	No regul.	Sync. (Sev. art.)	Zoom (note- taking facilities)
26	0	Yes	No	No	Unkn.	No	No	No	Sev. art.	No regul.	Both (Sev. art.)	0
27	0	Yes	Yes	0	0	Yes	No	No	0	0	Both (Sev. art.)	0
28	Unlim.	Yes	Yes	No	No role	No	No	No	No	No regul.	Both (Sev. art.)	Moodle Video- conferencing tools
29	Unlim.	Yes	No	No	No role	No	No	No	Sev. art. (Peer pres- ence via videocon- ferencing tool)	No regul.	Sync. (Sev. art.)	Adobe Con- nect/Big Blue But- ton
30	Unlim.	Yes	Yes	Yes	By the teacher	No	Yes (Manual guidance by the teacher)	No	Peer pres- ence	No regul.	Sync. (Text chat)	Screen sharing
31	0	Yes	Yes	Yes	Unkn.	No	No	No	No	No regul.	Async. (Other)	The MOOC tools attached to VRL
32	Lim.	Yes	Yes	No	No role	No	No	No	Sev. art. (Avatars)	No regul.	Sync. (Sev. art.)	Note- taking facilities
33	Lim.	Yes	Yes	Yes	Sev. possi- bilities	No	0	0	0	0	0	0

	34	0	Yes	Yes	Yes	Yes	By the teacher	No	Yes (Act. block.)	Act. of peers (Split screen, real-time visualization)	No regul.	Sync. (Sev. art.)	0
35	Unlim.	0	Yes	0	No	No role	No	No	No	No	No regul.	No com.	0
36	Unlim.	Yes	Yes	Yes	Yes	Sev. possibilities	No	No	No	Actions of peers (Shared screen)	No regul.	No com.	0
37	0	Yes	Yes	Yes	No	No role	0	Yes (Other)	0	0	0	Both (Sev. art.)	Note-taking facilities TeamViewer
38	Lim.	Yes	Yes	No	0	0	No	Yes (Script)	Sev. artif.	Regul. by teachers	Regul. by teachers	Sync. (Sev. art.)	0
39	0	Yes	Yes	Yes	No	No role	No	Yes (Other)	0	0	No regul.	Both (Sev. art.)	0
40	0	0	0	0	0	0	0	0	Sev. art.	0	0	Sync.	0
41	0	Yes	Yes	Yes	Yes	By the learner	No	No	Sev. art. (List of people, roles, screen sharing)	Sev. art.	No regul.	Sync. (Sev. art.)	Note-taking facilities
42	Unlim.	Yes	Yes	Yes	Yes	By the learner	No	No	Sev. art. (Presence via camera + actions via screen sharing)	Sev. art.	No regul.	Sync. (Sev. art.)	Note-taking facilities

43	Unlim.	Yes	Yes	No	No role	0	Yes (Act. block.)	Sev. art. (List of logged-in members, notifications and propagation of modification to workspaces)	No regul.	Sync. (Text chat)	Note-taking facilities
44	0	Yes	No	0	Unkn.	0	No	Peer act.	No regul.	0	Jupyter Notebook, GitLab, Padlet
45	Lim.	Yes	Yes	No	No role	Yes	No	Sev. art. (presence of teachers and peers)	Regul. by teachers (advices)	Sync. (Sev. art.)	0
46	Unlim.	Yes	0	No	No role	No	No	Sev. art. (Videoconferencing for presence of peers and teachers)	No regul.	Sync. (Sev. art.)	Moodle TeamViewer
47	Lim.	0	0	Yes	By the learner	0	0	0	0	0	0
48	Lim.	Yes	Yes	Yes	Unkn.	Yes	Yes (Manual guidance by the teacher)	Sev. art. (Presence of peers and teachers)	No regul.	Sync. (Sev. art.)	Zoom (Note-taking facilities)
49	Lim.	Yes	Yes	0	0	0	No	Act. of peers (Sharing btw. students)	No regul.	Sync. (Text chat)	0

50	Lim.	Yes	0	No	No role	0	No	Act. of peers (Actions of students who choose to be visible)	No regul.	No com.	0
51	Lim.	Yes	No	0	Unkn.	0	0	Sev. art.	0	Sync. (Text chat)	0
52	Unlim.	Yes	No	No	No role	No	No	Peer presence (Videoconferencing)	No regul.	Sync. (Sev. art.)	0
53	Lim.	Yes	0	No	0	0	No	Sev. art.	No regul.	Both (Sev. art.)	0
54	Lim.	Yes	No	No	No role	0	Yes (Script)	0	No regul.	Sync. (Audio)	0
55	Unlim.	0	0	No	No role	No	No	No	No regul.	No	eJournal (Similar to a mailbox)
56	Lim.	Yes	0	Yes	0	Yes	0	0	0	Both (Sev. art.)	0
57	Unlim.	Yes	Yes	No	No role	No	No	Sev. art. (Peers and teachers presence on the video tool)	Regul. by teachers (Tasks assigned)	Both (Sev. art.)	Whiteboard, file sharing, note-taking facilities
58	Lim.	0	0	Yes	By the learner	0	0	Sev. art.	No regul.	Sync. (Sev. art.)	0
59	Lim.	Yes	Yes	No	No role	No	No	Other	Regul. by learners (Verbal exchanges)	Sync. (Sev. art.)	The ones of Teams

60	Unlim.	Yes	Yes	Yes	Yes	No	No	No	Peer presence (Videoconferencing)	Regul. by learners (Give control of the lab to a student)	Both (Sev. art.)	Moodle
61	0	Yes	0	Yes	Unkn.	0	No	No	0	0	Both (Sev. art.)	Moodle + TeamViewer
62	0	Yes	Yes	No	No role	No	No	No	No	No regul.	Async. (Other)	Wiki
59	Lim.	Yes	Yes	No	No role	No	No	No	Other	Regul. by learners (Verbal exchanges)	Sync. (Sev. art.)	The ones of Teams
60	Unlim.	Yes	Yes	Yes	Sev. possibilities	No	No	No	Peer presence (Videoconferencing)	Regul. by learners (Give control of the lab to a student)	Both (Sev. art.)	Moodle
61	0	Yes	0	Yes	Unkn.	0	No	No	0	0	Both (Sev. art.)	Moodle + TeamViewer
62	0	Yes	Yes	No	No role	No	No	No	No	No regul.	Async. (Other)	Wiki

Abbreviations: collab. = collaboration; btw. = between; dist. = distinct; guid. = guidance; awar. = awareness; regul. = regulation; com. = communication; lim. = limited; unlim. = unlimited; act. block. = action blocking; sync. = synchronous; async. = asynchronous; unkn. = unknown; sev. art. = several artifacts

**C. Coding scheme of the reviewed publications for "Evaluation of collaboration and learning" category**

Nr.	Purpose of the evaluation	Data collected to measure collaboration	Type of indicator	Results	Study duration	Number of participants	Level of education	Learning measures	Impact of the VRL on learning
1	Impact of group formation, gender and academic level on collaboration, impact of gender composition of group on completion time	Quantitative	Gender and academic level using a single factor ANOVA, Tukey HSD test, two surveys	No significant difference between the sexes and between academic levels, students performed much better where they knew their group members, significant effect of collaborative group formation on participant interaction	0	72 (half girls - half boys)	Higher	Questions	Positive
2	Usability, UX, impact on collaboration	Qualitative	Survey	0	0	12	Higher	0	0

3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Utilisability	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Real-life test without protocol or results	0	0	0	0	0	0	0	0	0	0	0	0
10	Laboratory deployment	0	0	0	0	0	0	0	0	0	0	0	0
11	Pedagogical feasibility and effectiveness	0	0	0	0	0	0	0	0	0	0	0	0
12	No evaluation of the collaboration	0	0	0	0	0	0	0	0	0	0	0	0
13	Acceptance	Qualitative	User feedback	The competition-based environment reinforces learning, and the collaborative aspect offered by the 3D world is useful and appreciated.	0	0	0	0	0	0	0	0	0

	Collaboration	Quantitative	Questionnaire	Mental workload improved by the collaboration system and correlated with satisfaction	0	25	Higher	0	0
14									
15	Survey but no specific question on collaboration	0	0	0	0	0	0	Investigation	Positive
16	Learning and usability	0	0	0	0	0	0	Pre- and post-tests on knowledge	Positive
17	0	0	0	0	0	0	0	0	0
18	Satisfaction and performance	0	0	0	0	0	0	0	0
19	Examples of challenges addressed by students, use of Industry 4.0, type of technology used	0	0	0	0	0	0	0	0
20	Unknown	0	0	0	0	0	0	Unknown	Positive



25	Impact of collaboration and student demographics on student success	Qualitative	Learning outcomes, self-perceived learning, demographic questions	Collaboration had a significantly positive impact on student success, while demographics did not have an impact.	237	Higher	Learning outcomes of the experiment, self-perceived learning	Positive
26	Usability	0	0	0	0	0	0	0
27	Impact of the environment on the improvement of relationships and the development of cooperative competence	Qualitative	Questionnaires	Positive impact on communication, student's relationships and cooperative competence development	289	Higher	0	0

28	Network traffic, number of PC available, how and when the lab is used, whether students work together for solving exercises	Quantitative	Ratio between the total time when both group members were connected simultaneously and the overall total time when only one was connected	The sole possibility to work jointly in a group is sufficient to motivate students for group work.	2 courses, each lasting 50 days	80 in course A, 60 in course B	Higher	0	0
29	0	0	0	0	0	0	0	0	0
30	Perception and opinion of the remote labs	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0
32	Using the virtual laboratory	Quantitative	Laboratory activities	The whiteboard was used less than expected.	Several sessions	0	0	0	0
33	Satisfaction with the online device and overall perception of the system	0	0	0	0	0	0	0	0

	Feedback including collaboration	Qualitative	Questionnaire	Appreciate the use of popular videoconferencing software such as Skype alongside	0	25	Higher	Questionnaire	Positive
34									
35	No evaluation of the collaboration	0	0	0	0	0	0	0	0
36	No evaluation of the collaboration	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0
38	General assessment of the two improvement projects	0	0	0	0	0	0	0	0
39	Validity, Practicality	0	0	0	0	0	0	0	0
40	Learning, system functionality and pedagogical content	0	0	0	0	0	0	Questionnaire	Positive

41	Satisfaction, collaboration	Qualitative	User feedback	Language is a barrier because international students, Internet connection problems, regular interaction with classmates	3 weeks in 2014, 4 weeks in 2015	12 students in 2014, 14 students in 2015	Higher	0	0
42	Quality of experience, including teamwork	Qualitative	Questionnaire	The level of teamwork skills has improved	3 weeks in 2014, 4 weeks in 2015	12 students in 2014, 14 students in 2015	Higher	Feedback and questionnaire	Positive
43	Communication, collaboration systems, workspace	Qualitative	Questionnaire	Acceptable system, most participants had a positive experience of collaboration	0	34	0	0	0
44	0	0	0	0	0	0	0	Course evaluation	Positive
45	Learning outcomes and perception	0	0	0	0	0	0	Learning gain from pre- and post-tests	Positive



	Worksheet, activity, collaboration	Qualitative	Survey	Internet connection problems lead to chat being used to the detriment of video, resulting in a division of attention (reading the worksheet + chat), and therefore effort.	2 hours	12	Higher	Feedback	Positive
52									
53	Learning and teaching effectiveness	0	0	0	0	0	0	Learning outcome accomplishment and teaching effectiveness	Positive
54	Presence, immersion, engagement, comparison of VR/non-VR systems	0	0	0	0	0	0	0	0





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## References

- Ahmed, N., & Lataifeh, M. (2024). Impact and analysis of a collaborative augmented reality educational environment. *Journal of Computers in Education*, *11*, 697–719. <https://doi.org/10.1007/s40692-023-00275-x>
- Ahmed, N., Lataifeh, M., Alhamarna, A. F., Alnahdi, M. M., & Almansori, S. T. (2021). Learn: A collaborative learning environment using augmented reality. In: *2021 IEEE 2nd International Conference on Human-Machine Systems* (pp. 1–4). <https://doi.org/10.1109/ICHMS53169.2021.9582643>
- Aimran Wan Mohd Kamil, W. M., Abdul Hamid, N. S., Puteh, M., Hasan Sazalli, N. A., Ramly, L. Z., Mohamad, A. R., ..., Heintz, M. (2019). Using interactive applet to support collaborative learning of the hertzsprung-russell diagram. In: *2019 6th International Conference on Space Science and Communication* (pp. 163–167). <https://doi.org/10.1109/IconSpace.2019.8905949>
- Alghamdi, W. Y., Aljuaid, H. M., Alqessayer, K. N., Alshaikh, N. A., Alsofiany, W. A., Alnemari, O. T., & Alghamdi, M. M. (2024). Interactive tu-virtual labs. *Procedia Computer Science*, *251*, 164–169. <https://doi.org/10.1016/j.procs.2024.11.097>
- Alsaleh, S., Tepljakov, A., Köse, A., Belikov, J., & Petlenkov, E. (2022). Reimagine lab: Bridging the gap between hands-on, virtual and remote control engineering laboratories using digital twins and extended reality. *IEEE Access*, *10*, 89924–89943. <https://doi.org/10.1109/ACCESS.2022.3199371>
- Al-Zoubi, A., Castro, M., Shahroury, F. R., & Sancristobal, E. (2023). Impact of remote labs in preparing students for work 4.0. In: *2023 IEEE Global Engineering Education Conference* (pp. 1–8). <https://doi.org/10.1109/EDUCON54358.2023.10125216>
- Arora, R., Goel, S., & Mittal, R. K. (2017). Supporting collaborative software development in academic learning environment: A collaborative pair and quadruple programming based approach. In: *2017 Tenth International Conference on Contemporary Computing* (pp. 1–7). <https://doi.org/10.1109/IC3.2017.8284330>
- Arora, R., Maurya, A. M., Sharma, Y., & Kannan, M. (2022). A comprehensive framework and tool for supporting progressive learning of software development in an academic learning environment. *Computer Applications in Engineering Education*, *30*(2), 362–383. <https://doi.org/10.1002/cae.22460>
- Bardeen, M., & Wayne, M. (2016). E-labs - learning with authentic data. In: *EDULEARN16 Proceedings* (pp. 7495–7503). <https://doi.org/10.21125/edulearn.2016.0639>
- Barros, C., Leão, C. P., Soares, F., Minas, G., & Machado, J. (2013). RePhyS: A Multidisciplinary Experience in Remote Physiological Systems Laboratory. *International Journal of Online and Biomedical Engineering (iJOE)*, *9*(S5), 21–24. <https://doi.org/10.3991/ijoe.v9iS5.2756>
- Bedwell, W. L., Wildman, J. L., Granados, D. D., Salazar, M., Kramer, W. S., & Salas, E. (2012). Collaboration at work: An integrative multilevel conceptualization. *Human Resource Management Review*, *22*(2), 128–145. <https://doi.org/10.1016/j.hrmr.2011.11.007>
- Bell, T., Urhahne, D., Schanze, S., & Ploetzner, R. (2009). Collaborative inquiry learning: Models, tools, and challenges. *International Journal of Science Education*, *32*(3), 349–377. <https://doi.org/10.1080/09500690802582241>
- Bhute, V. J., Ingua, P., Shah, U., & Brechtelsbauer, C. (2021). Transforming traditional teaching laboratories for effective remote delivery-a review. *Education for Chemical Engineers*, *35*, 96–104. <https://doi.org/10.1016/j.ece.2021.01.008>

- Birkeland, H., Khalil, M., & Wasson, B. (2023). Understanding collaboration in virtual labs: A learning analytics framework development. In M. E. Auer, W. Pachatz, & T. Rüttemann (Eds.), *Learning in the age of digital and green transition* (pp. 192–203). Cham: Springer International Publishing.
- Bochicchio, M. A., Longo, A., Vaira, L., & Zappatore, M. (2015). Fostering online scientific experimentations in universities and high schools: The EDOC project. In: *2015 3rd Experiment International Conference (exp.at'15)* (pp. 337–342). <https://doi.org/10.1109/EXPAT.2015.7463291>
- Bochicchio, M. A., Longo, A., Zappatore, M., & Tarantino, D. (2015). A collaborative multi-videoconferencing platform for online optical microscopy. In: *Proceedings of 2015 12th International Conference on Remote Engineering and Virtual Instrumentation (REV)* (pp. 143–151). <https://doi.org/10.1109/REV.2015.7087281>
- Bochicchio, M. A., Longo, A., Zappatore, M., & Tarantino, D. (2016). The role of online labs in the European e-Science Infrastructure. In: *2016 13th International Conference on Remote Engineering and Virtual Instrumentation (REV)* (pp. 359–365). <https://doi.org/10.1109/REV.2016.7444503>
- Bogdanov, E., Salzmann, C., & Gillet, D. (2012). Widget-based approach for remote control labs. *IFAC Proceedings Volumes*, 45(11), 189–193. <https://doi.org/10.3182/20120619-3-RU-2024.00091>
- Bracq, M.-S., Michinov, E., & Jannin, P. (2019). Virtual reality simulation in nontechnical skills training for healthcare professionals: A systematic review. *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare*, 14(3), 188–194. <https://doi.org/10.1097/SIH.0000000000000347>
- Callaghan, M. J., McCusker, K., Losada, J. L., Harkin, J., & Wilson, S. (2013). Using game-based learning in virtual worlds to teach electronic and electrical engineering. *IEEE Transactions on Industrial Informatics*, 9(1), 575–584. <https://doi.org/10.1109/TII.2012.2221133>
- Carreón, G. A. G., Lugo, P. C., & Valencia, S. A. C. (2018). Teaching online laboratory based on cloud services. In: *2018 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)* (pp. 1–6). <https://doi.org/10.1109/ROPEC.2018.8661427>
- Chan, P., Van Gerven, T., Dubois, J.-L., & Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Computers & Education Open*, 2, Article 100053. <https://doi.org/10.1016/j.caeo.2021.100053>
- Chancharoen, R., & Phanomchoeng, G. (2022). The Telepresence Laboratory for a New Campus Life Since the Covid-19 Crisis. *International Journal of Engineering Education*, 38(5B), 1523–1535. Retrieved from <https://www.ijee.ie/contents/c380522B.html>
- Chang, Y., Aziz, E.-S., Esche, S. K., & Chassapis, C. (2011). A game-based laboratory for gear design. In: *2011 ASEE Annual Conference & Exposition* (pp. 22–43).
- Chen, J., Wang, M., Kirschner, P. A., & Tsai, C.-C. (2018). The role of collaboration, computer use, learning environments, and supporting strategies in cscl: A meta-analysis. *Review of Educational Research*, 88(6), 799–843. <https://doi.org/10.3102/0034654318791584>
- Cibuljska, E., & Boločko, K. (2024). Collaborative virtual reality environment structural model development for higher education remote learning. In M. E. Auer & T. Tsiatsos (Eds.), *Smart mobile communication & artificial intelligence* (pp. 61–68). Cham: Springer Nature Switzerland.
- Ciolacu, M. I., Marcu, A.-E., Vladescu, M., Stoichescu, D., & Svasta, P. (2021). Education 4.0 Lab for Digital Innovation Units – Collaborative Learning in Time of COVID-19 Pandemic. In: *2021 IEEE 27th International Symposium for Design and Technology in Electronic Packaging (SIITME)* (pp. 268–271). <https://doi.org/10.1109/SIITME53254.2021.9663606>
- Coelho, P. A., Casanello, F., Leal, N., Brintrup, K., Angulo, L., Sanhueza, I., ..., Forcael, E. (2024). Challenge-based learning and scrum as enablers of 4.0 technologies in engineering education. *Applied Sciences-Basel*, 14(21). <https://doi.org/10.3390/app14219746>
- Corbi, A., Burgos, D., Vidal, F., Albiol, K., & Albiol, A. (2019). X-ray imaging virtual online laboratory for engineering undergraduates. *European Journal of Physics*, 41, Article 014001. <https://doi.org/10.1088/1361-6404/ab5011>
- Corter, J., Esche, S., Chassapis, C., Ma, J., & Nickerson, J. (2011). Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. *Computers & Education*, 57, 2054–2067. <https://doi.org/10.1016/j.compedu.2011.04.009>
- De La Torre, L., Heradio, R., Jara, C. A., Sanchez, J., Dormido, S., Torres, F., & Candelas, F. A. (2013). Providing collaborative support to virtual and remote laboratories. *IEEE Transactions on Learning Technologies*, 6(4), 312–323. <https://doi.org/10.1109/TLT.2013.20>
- De Prada, E., Mareque, M., & Pino-Juste, M. (2022). Teamwork skills in higher education: Is university training contributing to their mastery? *Psicol. Refl. Crit.*, 35, 5. <https://doi.org/10.1186/s41155-022-00207-1>
- Desai, K., Belmonte, U. H. H., Jin, R., Prabhakaran, B., Diehl, P., Ramirez, V. A., ..., Gans, M. (2017). Experiences with Multi-modal Collaborative Virtual Laboratory (MMCVL). In: *2017 IEEE Third International Conference on Multimedia Big Data (BigMM)* (pp. 376–383). <https://doi.org/10.1109/BigMM.2017.62>


- Dillenbourg, P., & Tchounikine, P. (2007). Flexibility in macro-scripts for computer-supported collaborative learning. *Journal of Computer Assisted Learning*, 23(1), 1–13. <https://doi.org/10.1111/j.1365-2729.2007.00191.x>
- Dillenbourg, P. (1999). What do you mean by collaborative learning? In P. Dillenbourg (Ed.), *Collaborative-learning: Cognitive and computational approaches* (pp. 1–19). Oxford: Elsevier.
- Dong, J., & Guo, H. (2011). Enhance Computer Network Curriculum using Collaborative Project-based Learning. In: *Proceedings of the American Society for Engineering Education (ASEE) Conference*.
- Douar, A., Mahieddine, D., Harous, S., & Adel, A. (2023). 3DVL@ES: A 3D WebBased Virtual Laboratory for Collaborative Learning in Experimental Science Practical Work. *International Journal of e-Collaboration*, 19(1), 1–26. <https://doi.org/10.4018/IJeC.315786>
- Drysdale, T. D., & Braithwaite, N. S. J. (2017). An Internet of laboratory things. In: *2017 4th Experiment@International Conference (exp.at'17)* (pp. 236–240). <https://doi.org/10.1109/EXPAT.2017.7984362>
- Du, X., Dai, M., Tang, H., Hung, J.-L., Li, H., & Zheng, J. (2023). A multimodal analysis of college students' collaborative problem solving in virtual experimentation activities: A perspective of cognitive load. *Journal of Computing in Higher Education*, 35(2), 272–295. <https://doi.org/10.1007/s12528-022-09311-8>
- Duit, R., & Treagust, D. (1998). Learning in Science - From Behaviourism Towards Social Constructivism and Beyond. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 3–25). Dordrecht: Springer.
- Dutton, N. A. (2023). A novel approach to an online microbiology experiment yields greater student success. *American Journal of Distance Education*, 37(2), 85–95. <https://doi.org/10.1080/08923647.2022.2157627>
- Estriégana, R., Medina, J., Ramirez, R., & Barchino, R. (2021). Analysis of cooperative skills development through relational coordination in a gamified online learning environment. *Electronics*, 10, 2032. <https://doi.org/10.3390/electronics10162032>
- Fabini, J., Hartl, A., Meghdouri, F., Breitenfellner, C., & Zseby, T. (2021). SecTULab: A Moodle-Integrated Secure Remote Access Architecture for Cyber Security Laboratories. In: *Proceedings of the 16th International Conference on Availability, Reliability and Security*. <https://doi.org/10.1145/3465481.3470034>
- Farah, S., Benachenhou, A., Neveux, G., Barataud, D., Andrieu, G., & Fredon, T. (2015). Real-time microwave remote laboratory architecture. In: *2015 European Microwave Conference (EuMC)* (pp. 1315–1318). <https://doi.org/10.1109/EuMC.2015.7346013>
- Farah, S., Abdelhalim, B., Guillaume, N., Barataud, D., Andrieu, G., & Fredon, T. (2016). Multi-user and real-time flexible remote laboratory architecture for collaborative and cooperative pedagogical scenarios. *International Journal of Online Engineering (iJOE)*, 12, 33. <https://doi.org/10.3991/ijoe.v12i04.5097>
- Giere, R. N., & Moffatt, B. (2003). Distributed cognition: Where the cognitive and the social merge. *Social studies of science*, 33(2), 301–310.
- Gleich, D., Sarjaš, A., Malajner, M., Miteva, P., Josifovska, J. S., Bozinovska, N., ..., Pavosević, M. (2020). CORELA Collaborative Learning Environment for Electrical Engineering Education. In: *2020 international conference on systems, signals and image processing (iwSSIP)* (pp. 169–172). <https://doi.org/10.1109/IWSSIP48289.2020.9145082>
- González Rodrigo, B., Mosquera Feijoo, J., Ramirez Masferrer, J., Fernández-Ordoñez Hernández, D., & Fernández Avilés, D. (2014). The virtual room as an opportunity to support collaborative learning in the area of knowledge of continuum mechanics. *ICERI2014 Proceedings* (pp. 1764–1768). IATED: Seville, Spain.
- Govaerts, S., Cao, Y., Vozniuk, A., Holzer, A., Zutin, D. G., Ruiz, E. S. C., ..., & Gillet, D. (2013). Towards an online lab portal for inquiry-based stem learning at school. In: *Advances in Web-Based Learning - ICWL 2013* (pp. 244–253). Springer, Berlin Heidelberg: Berlin, Heidelberg.
- Gravier, C., Fayolle, J., & Lardon O'Connor, M. J. (2012). Adaptive system for collaborative online laboratories. *IEEE Intelligent Systems*, 27(4), 11–17. <https://doi.org/10.1109/MIS.2011.1>
- Hazlehurst, B., Gorman, P. N., & McMullen, C. K. (2008). Distributed cognition: An alternative model of cognition for medical informatics. *International journal of medical informatics*, 77(4), 226–234.
- Hernández-de-Menéndez, M., Vallejo Guevara, A., & Morales-Menendez, R. (2019). Virtual reality laboratories: A review of experiences. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 13, 947–966. <https://doi.org/10.1007/s12008-019-00558-7>
- Hernández-Sellés, N., Muñoz-Carril, P.-C., & González-Sanmamed, M. (2019). Computer-supported collaborative learning: An analysis of the relationship between interaction, emotional support and online collaborative tools. *Computers & Education*, 138, 1–12. <https://doi.org/10.1016/j.compedu.2019.04.012>

- Hesse, F., Care, E., Buder, J., Sassenberg, K., & Griffin, P. (2015). A framework for teachable collaborative problem solving skills. In P. Griffin & E. Care (Eds.), *Assessment and Teaching of 21st Century Skills: Methods and Approach* (pp. 37–56). Dordrecht: Springer, Netherlands.
- Hmelo-Silver, C. E., & Jeong, H. (2021). Benefits and challenges of interdisciplinarity in cscl research: A view from the literature. *Frontiers in Psychology, 11*, Article 579986. <https://doi.org/10.3389/fpsyg.2020.579986>
- Howard-Jones, P., Ott, M., van Leeuwen, T., & de Smedt, B. (2014). The potential relevance of cognitive neuroscience for the development and use of technology-enhanced learning. *Learning, Media and Technology, 40*(2), 131–151. <https://doi.org/10.1080/17439884.2014.919321>
- Hutchins, E. (2000). Distributed cognition. *International encyclopedia of the social and behavioral sciences, 138*(1), 1–10.
- Jara, C. A., Candelas, F. A., Torres, F., Dormido, S., & Esquembre, F. (2012). Synchronous collaboration of virtual and remote laboratories. *Computer Applications in Engineering Education, 20*(1), 124–136. <https://doi.org/10.1002/cae.20380>
- Jara, C. A., Candelas, F. A., Torres, F., Salzmann, C., Gillet, D., Esquembre, F., & Dormido, S. (2012). Synchronous collaboration between autogenerated webgl applications and 3d virtual laboratories created with easy java simulations. *IFAC Proceedings Volumes, 45*(11), 160–165. <https://doi.org/10.3182/20120619-3-RU-2024.00039>
- Jara, C. A., Heradio, R., Torre, L., d. I., Sanchez, J., Dormido, S., Torres, F., & Candelas, F. A. (2012). Synchronous collaboration with virtual and remote labs in moodle. *IFAC Proceedings Volumes, 45*(11), 270–275. <https://doi.org/10.3182/20120619-3-RU-2024.00030>
- Järvelä, S., Kirschner, P. A., Panadero, E., Malmberg, J., Phielix, C., Jaspers, J., Koivuniemi, M., & Järvenoja, H. (2015). Enhancing socially shared regulation in collaborative learning groups: Designing for cscl regulation tools. *Educational Technology Research and Development, 63*(1), 125–142. <https://doi.org/10.1007/s11423-014-9358-1>
- Jeong, H., & Hmelo-Silver, C. E. (2016). Seven affordances of computer-supported collaborative learning: How to support collaborative learning? how can technologies help? *Educational Psychologist, 51* (2), 247–265. <https://doi.org/10.1080/00461520.2016.1158654>
- Jiun, L., Kamarudin, N., Hassan, A., & Talib, O. (2014). Inquiry-based learning in laboratory science. In: *Graduate Research in Education Conference (GREDUC2014)*.
- Kirschner, P. A., Sweller, J., Kirschner, F., Zambrano, R., & J. (2018). From cognitive load theory to collaborative cognitive load theory. *International Journal of Computer-Supported Collaborative Learning, 13*, 213–233. <https://doi.org/10.1007/s11412-018-9277-y>
- Kostic, Z. (2015). Web-based laboratory for collaborative and concurrent cad designing, assembling, and practical exercising on distance. *Tehnicki vjesnik-Technical Gazette, 22*, 591–597. <https://doi.org/10.17559/TV-20140211115630>
- Kostic, Z., Cvetković, D., Jevremović, A., Radakovic, D., Popović, R., & Markovic, D. (2013). The development of assembly constraints within a virtual laboratory for collaborative learning in industrial design. *Tehnicki Vjesnik, 20* (5), 747–753. Retrieved from <https://hrcak.srce.hr/109781>
- Leblond, L., & Hicks, M. (2021). Designing laboratories for online instruction using the iolab device. *The Physics Teacher, 59*(5), 351–355. <https://doi.org/10.1119/10.0004886>
- Leinonen, T., Muukkonen, H., Hakkarainen, K., & Mielonen, S. (2000). *Supporting learning communities in education*. Helsinki: University of Art and Design and University of Helsinki.
- Lindsay, E., Long, P., & Imbrie, P. (2007). Workshop - remote laboratories: Approaches for the future. In: *2007 37th Annual Frontiers In Education Conference - Global Engineering: Knowledge Without Borders, Opportunities Without Passports (WIC-1-WIC-2)*. <https://doi.org/10.1109/FIE.2007.4418239>
- Ma, J., & Nickerson, J. V. (2006). Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Comput. Surv., 38* (3), 7–es. <https://doi.org/10.1145/1132960.1132961>
- Maarouf, S., Radhi, M., Vahé, N., Moustapha, D. A., Hamadou, S.-H., Sandra, S., ..., Gérald, B. (2012). Collaborative activities in the remote laboratory work. In: *2012 15th International Conference on Interactive Collaborative Learning (ICL)* (pp. 1–6). <https://doi.org/10.1109/ICL.2012.6402175>
- Masril, M., Jalinus, N., Ridwan, Ambiyar, Sukardi, & Irfan, D. (2024). A flexible practicum model on education: Hybrid learning integrated remote laboratory activity design. *International Journal of Online and Biomedical Engineering, 20*(10), 4–17. <https://doi.org/10.3991/ijoe.v20i10.48031>
- Mateescu, M., Pimmer, C., Zahn, C., Klinkhammer, D., & Reiterer, H. (2019). Collaboration on large interactive displays: A systematic review. *Human-Computer Interaction, 36*, 1–35. <https://doi.org/10.1080/07370024.2019.1697697>
- May, D., Jahnke, I., & Moore, S. (2023). Online laboratories and virtual experimentation in higher education from a sociotechnical-pedagogical design perspective. *J Comput High Educ, 35*, 203–222. <https://doi.org/10.1007/s12528-023-09380-3>

- May, D. (2020). Cross reality spaces in engineering education – online laboratories for supporting international student collaboration in merging realities. *International Journal of Online Engineering (iJOE)*, 16, 4. <https://doi.org/10.3991/ijoe.v16i03.12849>
- May, D., Sadiki, A., Pleul, C., & Tekkaya, A. E. (2015). Teaching and learning globally connected using live online classes for preparing international engineering students for transnational collaboration and for studying in germany. In: *Proceedings of 2015 12th International Conference on Remote Engineering and Virtual Instrumentation (REV)* (pp. 118–126). <https://doi.org/10.1109/REV.2015.7087275>
- May, D., & Tekkaya, A. (2016). Transnational connected learning and experimentation - using live online classes and remote labs for preparing international engineering students for an international working world. *International Journal of Online Engineering (iJOE)*, 6, 18. <https://doi.org/10.3991/ijep.v6i1.5287>
- Mechta, D., Harous, S., & Djoudi, M. (2022). Tele-Collaboration System in CVLab. *Informatica*, 46(2), 223–233. <https://doi.org/10.31449/inf.v46i2.3205>
- Meier, A., Spada, H., & Nikol, R. (2007). A rating scheme for assessing the quality of computer-supported collaboration processes. *Computer Supported Learning*, 2, 63–86. <https://doi.org/10.1007/s11412-006-9005-x>
- Miller, E., Ceballos, H., Engelmann, B., Schiffler, A., Batres, R., & Schmitt, J. (2021). Industry 4.0 and international collaborative online learning in a higher education course on machine learning. In: *2021 Machine Learning-Driven Digital Technologies for Educational Innovation Workshop* (pp. 1–8). <https://doi.org/10.1109/IEEECONF53024.2021.9733776>
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The prisma statement. *PLoS Med*, 6(7), Article e1000097. <https://doi.org/10.1371/journal.pmed.1000097>
- Muchlas, & Novianta, M. A. (2015). An online lab for digital electronics course using information technology supports. In: *2015 International Conference on Science in Information Technology (ICSITech)* (pp. 299–302). <https://doi.org/10.1109/ICSITech.2015.7407821>
- Mulya, R., Krismadinata, K., Jalinus, N., & Effendi, H. (2021). Practical work of digital system course based on virtual laboratory. *International Journal of Online and Biomedical Engineering (iJOE)*, 17, 22. <https://doi.org/10.3991/ijoe.v17i08.23359>
- Nedic, Z. (2012). Demonstration of collaborative features of remote laboratory netlab. In: *2012 9th International Conference on Remote Engineering and Virtual Instrumentation (REV)* (pp. 1–4). <https://doi.org/10.1109/REV.2012.6293179>
- Ng, D. T. K. (2022). Online lab design for aviation engineering students in higher education: A pilot study. *Interactive Learning Environments*, 31(10), 6317–6334. <https://doi.org/10.1080/10494820.2022.2034888>
- Odeh, S., & Ketaneh, E. (2012). E-collaborative remote engineering labs. In: *Proceedings of the 2012 IEEE Global Engineering Education Conference (EDUCON)* (pp. 1–10). <https://doi.org/10.1109/EDUCON.2012.6201126>
- Olson, G. M., & Olson, J. S. (2000). Distance matters. *Human-Computer Interaction*, 15(2–3), 139–178. [https://doi.org/10.1207/S15327051HCI1523\\_4](https://doi.org/10.1207/S15327051HCI1523_4)
- Oyarzun, B., & Martin, F. (2023). A systematic review of research on online learner collaboration from 2012–21: Collaboration technologies, design, facilitation, and outcomes. *Online Learning Journal*, 27, 71–106. <https://doi.org/10.24059/olj.v27i1.3407>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ..., Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, 372. <https://doi.org/10.1136/bmj.n71>, <https://www.bmj.com/content/372/bmj.n71.full.pdf>
- Panicker, R. C., & John, D. (2021). Fully remote project-based learning of hardware/software codesign. In: *2021 IEEE Frontiers in Education Conference (FIE)* (pp. 1–5). <https://doi.org/10.1109/FIE49875.2021.9637053>
- Patacsil, F., & Tablatin, C. (2017). Exploring the importance of soft and hard skills as perceived by it internship students and industry: A gap analysis. *Journal of Technology and Science Education*, 7, 347. <https://doi.org/10.3926/jotse.271>
- Pirker, J., Holly, M. S., Hipp, P., König, C., Jeitler, D., & Gütl, C. (2018). Improving physics education through different immersive and engaging laboratory setups. In M. E. Auer & T. Tsiatsos (Eds.), *Interactive mobile communication technologies and learning* (pp. 443–454). Cham: Springer International Publishing.
- Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, 95, 309–327. <https://doi.org/10.1016/j.compedu.2016.02.002>
- Raman, R., Achuthan, K., Nair, V., & Nedungadi, P. (2022). Virtual laboratories - a historical review and bibliometric analysis of the past three decades. *Educ Inf Technol*, 27, 11055–11087. <https://doi.org/10.1007/s10639-022-11058-9>

- Restivo, M. T., Mendes, J., Lopes, A. M., Silva, C. M., & Chouzal, F. (2009). A remote laboratory in engineering measurement. *IEEE Transactions on Industrial Electronics*, 56(12), 4836–4843. <https://doi.org/10.1109/TIE.2008.2011479>
- Richter, T., Boehringer, D., & Jeschke, S. (2011). Lila: A european project on networked experiments. In S. Jeschke, I. Isenhardt, & K. Henning (Eds.), *Automation, communication and cybernetics in science and engineering 2009/2010* (pp. 307–317). Berlin, Heidelberg: Springer, Berlin Heidelberg.
- Rivas, J. L., Guzmán, J. L., Rodríguez, F., Berenguel, M., & Dormido, S. (2012). Integrated virtual and remote lab for greenhouse climate control. *IFAC Proceedings Volumes*, 45(11), 264–269. <https://doi.org/10.3182/20120619-3-RU-2024.00025>
- Roda-Segarra, J. (2021). Virtual laboratories during the covid-19 pandemic: A systematic review. In: *2021 XI International Conference on Virtual Campus (JICV)* (pp. 1–4). <https://doi.org/10.1109/JICV53222.2021.9600344>
- Rogers, Y. (1997). A brief introduction to distributed cognition. Retrieved June 26, 2025, from <https://api.semanticscholar.org/CorpusID:13635589>
- Rosen, Y., Wolf, I., & Stoeffler, K. (2020). Fostering collaborative problem solving skills in science: The animalia project. *Computers in Human Behavior*, 104, Article 105922. <https://doi.org/10.1016/j.chb.2019.02.018>
- Saab, N., Van Joolingen, W., & Van Hout-Wolters, B. (2012). Support of the collaborative inquiry learning process: Influence of support on task and team regulation. *Metacognition and Learning*, 7(1), 7–23. <https://doi.org/10.1007/s11409-011-9068-6>
- Saliyah-Hassane, H., Saad, M., Ofosu, W., Karimou, D., Hassane, A., & Dodo Amadou, M. (2011). Lab@Home: Remote Laboratory Evolution in the Cloud Computing Era. In: *American Society for Engineering Education Annual Conference*. <https://doi.org/10.18260/1-2--18691>
- Schnaubert, L., & Vogel, F. (2022). Integrating collaboration scripts, group awareness, and self-regulation in computer-supported collaborative learning. *International Journal of Computer-Supported Collaborative Learning*, 17, 1–10. <https://doi.org/10.1007/s11412-022-09367-9>
- Scouler, C., Duckworth, D., Heard, J., & Ramalingam, D. (2020). *Collaboration: Definition and structure*. Australian Council for Educational Research: Camberwell.
- Shah, U., Inguva, P., Tan, B., Yuwono, H., Bhute, V. J., Campbell, J., Macey, A., & Brechtelsbauer, C. (2021). Create labs - student centric hybrid teaching laboratories. *Education for Chemical Engineers*, 37, 22–28. <https://doi.org/10.1016/j.ece.2021.07.004>
- Stahl, G. (2021). *Theoretical investigations: Philosophical foundations of group cognition*. Cham: Springer International Publishing.
- Straus, S., & Rummel, N. (2021). Promoting regulation of equal participation in online collaboration by combining a group awareness tool and adaptive prompts. but does it even matter? *International Journal of Computer-Supported Collaborative Learning*, 16 (1), 67–104. <https://doi.org/10.1007/s11412-021-09340-y>
- Strauß, S., & Rummel, N. (2023). Feed-back about the collaboration process from a group awareness tool. potential boundary conditions for effective regulation. In: O. Noroozi & B. DeWever (Eds.), *The power of peer learning: Fostering students' learning processes and outcomes* (pp. 183–213). Springer International Publishing.
- Teng, L., Tang, Y. M., Wu, R. P., Tsui, G. C., Tsang, Y. P., & Tang, C. Y. (2024). Exploring the efficacy of collaborative learning in a remote robotics laboratory: A comparative analysis of performance and pedagogical approaches. *Smart Learning Environments*, 11, 15. <https://doi.org/10.1186/s40561-024-00305-w>
- Tripepi, M. (2022). Microbiology laboratory simulations: From a last-minute resource during the covid-19 pandemic to a valuable learning tool to retain-a semester microbiology laboratory curriculum that uses labster as prelaboratory activity. *Journal of Microbiology and Biology Education*, 23(1), e00269-21. <https://doi.org/10.1128/jmbe.00269-21>
- Vodovozov, V., Raud, Z., & Lehtla, T. (2015). Active learning in remote electrical drive laboratory. In: *2015 IEEE Global Engineering Education Conference (EDUCON)* (pp. 28–34). <https://doi.org/10.1109/EDUCON.2015.7095946>
- Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge: Harvard University Press.
- Wang, N., Chen, X., Lan, Q., Song, G., Parsaei, H. R., & Ho, S.-C. (2017). A Novel Wiki-Based Remote Laboratory Platform for Engineering Education. *IEEE Transactions on Learning Technologies*, 10(3), 331–341. <https://doi.org/10.1109/TLT.2016.2593461>
- Zhang, Z., Zhang, M., Chang, Y., Aziz, E.-S., Esche, S. K., & Chassapis, C. (2018). Collaborative virtual laboratory environments with hardware in the loop. In M. E. Auer, A. K. Azad, A. Edwards, & T. De Jong (Eds.), *Cyber-physical laboratories in engineering and science education* (pp. 363–402). Cham: Springer International Publishing.

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