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# Virtual Laboratories in STEM Higher Education: A Scoping Review

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**ABSTRACT**
Synthetic learning environments like virtual laboratories are increasingly used in pedagogical practice across the landscape of higher education, in both professional and non-professional study programs. Virtual laboratories are simulations of experiments or other hands-on activities that allow students to explore scientific concepts and principles in a virtual environment. These simulations can be used to supplement or replace traditional laboratory experiences on campus, providing students with a flexible and convenient way to learn and engage with the laboratory as a context for work. The conceptual and theoretical foundations of these simulations, however, are still poorly understood. This study provides a scoping review of the literature on how virtual laboratories are conceptualized in STEM higher education, and the ideas, principles and presuppositions that inform and sustain research on virtual laboratories in STEM. By searching through databases ($n$ = 7) for peer-reviewed journal articles published in English between 2012 and 2023, focusing on the use of virtual laboratories in STEM higher education, a selection of articles ($n$ = 23) was identified as relevant for the study aim and subjected to thematic analysis and narrative synthesis. The results add to our knowledge from previous systematic reviews of studies on virtual laboratories in STEM higher education, particularly by identifying common characteristics between various definitions of virtual laboratories. Moreover, the review identifies three theoretical traditions influencing work on virtual laboratories for STEM in higher education. While this highlights a field of research committed to evidence-informed pedagogy and instructional effectiveness, it also points to a lack of descriptive, qualitative research that systematically investigates everyday instructional practices with virtual laboratories in STEM-education in naturalistic contexts. Further studies on what happens in such settings would be valuable for informing future theorizing about virtual laboratories in STEM.

**Keywords:** *virtual laboratories; STEM; higher education; scoping literature review; narrative synthesis*

### Highlights

The review found that there is a lack of a joint definition of virtual laboratories in the literature, but that there are common characteristics between definitions, including functionality, interactivity, and experiential aspects of virtual laboratories.

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The review identified a limited number of studies that explicitly adopted theoretical perspectives on learning. From those that did, we identify three main theoretical strands: embodiment and experiential learning, social cognitivist theories, and constructivist theories of learning.

The reviewed articles focused mainly on evaluating the effectiveness of virtual laboratories as a pedagogical intervention and informing their design.

To inform future theorizing, there is a need for more descriptive, qualitative research that systematically investigates instructional practices related to the everyday use of virtual laboratories in STEM-education.

## 1 Introduction

Laboratory work has been described as a key component and a degree requirement in education for students in STEM (science, technology, engineering, and mathematics) higher education (Reeves & Crippen, 2021). However, recent developments like increased demands for distance education have led to the emergence of virtual laboratories, providing students with hands-on learning experiences without a need for the physical lab equipment that is traditionally offered in teaching laboratories at universities (Brinson, 2015; Makransky et al., 2016; Potkonjak et al., 2016). Virtual laboratories can be described as technology-mediated learning contexts situated within either two-dimensional (2D) desktop-based simulations, or three-dimensional (3D) virtual reality (VR) environments consisting of head mounted displays (Reeves & Crippen, 2021). Theoretically, we consider these pedagogical practices and instructional designs as belonging to a larger family of "synthetic learning environments" (Cannon-Bowers & Bowers, 2009): training milieus characterized by the orchestration of particular technologies, subject matters, and learner characteristics in gamified, virtual, or semi-virtual worlds. Use of synthetic learning environments like virtual labs in STEM higher education makes it possible for educators and students to simulate experiments that otherwise must be performed in a teaching laboratory, provide learners with an interactive experience that allows them to test hypotheses, collect data, and analyze results through the manipulation of virtual equipment and materials (Brinson, 2015; Reeves & Crippen, 2021).

This scoping review builds on previous literature reviews that outline the use of virtual laboratories in STEM, with the aim of advancing our conceptual understanding of this group of synthetic learning environments. Brinson (2015) conducted a review of empirical studies ($n$ = 56) between 2005 and 2015 which compares the use of virtual laboratories to traditional teaching laboratories, focusing the comparison on learning outcomes for different modalities. Brinson's review (2015) found that students can achieve learning outcomes with either traditional teaching laboratories or virtual laboratories at similar or better rates, depending on the outcome being measured, showing a striking lack of consensus regarding the effectiveness of virtual laboratories in science education. As a result, Brinson (2015) highlights the importance for future research to measure the effectiveness of laboratory type instruction relative to student grade level and cognitive development. Moreover, Brinson (2015) also expresses optimism in technical developments toward more interactive and immersive virtual laboratories to provide for more efficient learning experiences in the future. In a review one year later, Potkonjak et al. (2016) outlines the state-of-the art of virtual laboratories in STEM. By emphasizing that operating a virtual laboratory "must feel like they [students] are working with real authentic devices in a real authentic space," Potkonjak et al. (2016, p. 311) showcases a wide range of virtual learning environments: from robotic engineering laboratories and automated production systems towards Second Life and RealXtend, i.e., platforms that allow users to create and interact with avatars, objects, and environments in a virtual world. While Potkonjak et al. (2016) emphasize that technology and pedagogy mutually co-evolve, pedagogical issues fell outside the scope of their review. In Reeves and Crippen (2020), articles published between 2009 and 2019 on the use of virtual laboratories in science and engineering were reviewed using what they call a "systematic review" approach. The focus of this review was contextual characteristics, types of activities, and outcomes explored in previous studies, as well as the goals, perspectives, and interpretations used in this genre of research. Reeves and Crippen's (2020) review reveals a lack of consistent definitions of virtual laboratories, and nearly half of the 25 articles included in their review lack a theoretical perspective appropriate for interpreting student outcomes.[1] Instead, most of the studies included in their review aimed at evaluating the effectiveness of virtual laboratories, without any interaction with a human teacher or fellow students who had used the educational technology.

The increasing popularity of technology-driven teaching methods like virtual labs should, however, motivate a better understanding of their conceptual foundations, as these are ill-understood. This scoping review therefore aims to deepen the conceptual and theoretical base of this field by specifically investigating how virtual laboratories are conceptualized in research on STEM higher education, and the role of instructional theories in this landscape. The following research questions guide the study:

- RQ1. How are virtual laboratories conceptualized in the literature on STEM higher education?
- RQ2. Which instructional theories inform the literature on virtual laboratories in STEM higher education?

As these two research questions suggest, our scoping review seeks to identify and clarify "key concepts" and their "key characteristics" in the literature on virtual labs in STEM, following Munn et al.'s typology of key aims and indications for scoping reviews (2018; see also Tricco et al., 2016a). In comparison to systematic reviews as a

[1] While the study by Reeves and Crippen (2020) is subtitled a "systematic review," the indications listed by Munn et al. (2018) suggest that it could be classified within the broader genre of scoping reviews.

genre, which aims to systematically and comprehensively assess the state of evidence on a specific research question (as defined by narrow criteria), scoping reviews have broader epistemic aims, such as mapping the current state of research on a topic (see Arksey & O'Malley, 2005; Munn et al., 2018), including clarifying conceptual problems. This review genre is therefore particularly apt when the goal is to interrogate central concepts in the field of virtual laboratories in STEM, and for analyzing the role of instructional theories in this body of work, rather than examining the state and quality of evidence.

By examining articles published in academic journals over the past ten years, this scoping review presents a narrative synthesis of 23 articles on the use of virtual laboratories in STEM education, offering insights into a broad field of research where knowledge historically has been siloed between different disciplines (Brinson, 2017).

## 2 The scoping review method

To document our search, we adopted the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist (Tricco et al., 2018). Hence, the methods section reports on the following items: eligibility criteria (Section 2.1), information sources and search strategies (Section 2.2.) and the screening process (Section 2.3).

### *2.1 Eligibility criteria*

The following criteria were specified to identify current and high-quality empirical research of relevance for the study aims and research questions (see Table 1).

*Table 1.* Inclusion and exclusion criteria

| Inclusion criteria | Exclusion criteria |
|---|---|
| Journal articles | Conference papers, book chapters, dissertations and gray literature |
| Published 2012–2023 | Published before 2012 |
| Published in English | Language other than English |
| Empirical work | Literature reviews or conceptual papers |
| Focus on virtual labs | Full scale simulations, augmented reality (AR) |
| Focus on virtual labs for educational purposes | Simulations for non-educational purposes |
| Focus on STEM disciplines (science, technology, engineering, mathematics) | Focus outside the STEM disciplines (science, technology, engineering and mathematics) |
| Focus on higher education | Focus on STEM in K-12 education |

Similar to Reeves and Crippens (2021), we considered journal articles as the most relevant for inclusion, since articles in journals tend to undergo a rigid peer-review process prior to publication.

### *2.2 Information sources and search strategies*

Designing an effective search strategy for a scoping review includes balancing between creating a search string that is open enough to cover an appropriate number of studies, and specific enough to find studies of relevance for the research questions in focus. In order to achieve this, the first author used the core concepts of the study as search terms, starting with the most central terms and adding synonyms to narrow the scope, until the test searches yielded a suitable number of studies. As a commonly used concept in pedagogical research, we chose "STEM" as one of these core concepts, together with different variations describing the virtual tools in use as well as different variations of learning (see e.g., Reeves & Crippen, 2021). After pilot testing several variations of the search string, searches were conducted by the second author using the following search words: virtual lab OR sim* OR VR AND STEM AND higher education OR university students AND train* OR learn* OR assess*. However, the search could not be carried out in the exact same manner for all databases due to differences in their design and functionality. Hence slight variations between searches can be found, as reported below (see Table 2). Additional motivation for centering our scoping review around the STEM-acronym can be found in section 2.4 (Limitations).

The literature search was supported by the expertise of the librarians at the Education Library at the University of Gothenburg, during September 2022. The following databases were identified as most relevant for the research field and screened for studies: Scopus, ScienceDirect, PubMed, ERIC (Ebsco), ERIC (ProQuest), CINAHL, and The Cochrane Library.

*Table 2.* Structured searches in selected databases

| Data base | Search string | Criteria |
|---|---|---|
| Scopus | virtual lab OR sim* OR VR AND STEM AND higher education OR university students AND train* OR learn* OR assess* | date and journal article |
| Science Direct | ("virtual lab" OR simulation) AND (STEM) AND ("higher education") AND (learning) | date and research articles |
| PubMed | (virtual lab OR simulation OR VR) AND STEM AND (higher education OR university students) AND (training OR learning OR assess) | date |
| ERIC (Ebsco) | "virtual lab" OR sim* OR VR AND STEM AND "higher education" OR "university students" AND train* OR learn* OR assess* | date, language and academic journal |
| ERIC (PROQuest) | "virtual lab" OR sim* OR VR AND STEM AND "higher education" OR "university students" AND train* OR learn* OR assess* | date, language and journal scholarly |
| The Cochrane Library | (virtual lab OR sim* OR VR) AND (STEM) AND (higher education OR university students) AND (train* OR learn* OR assess*) | date |

In total, the database search identified 1,181 articles for screening. In addition, a small corpus of studies was included in the review based on early and less structured searches on the use of virtual labs in biomedical education ($n$ = 4). A new search was conducted in May 2023, which resulted in one additional study meeting the inclusion criteria and being included in the review (see Table 3).

### *2.3 Selection of sources of evidence*

In the first step of screening, the second author examined titles, keywords, and abstracts of the identified articles. In this phase, articles were excluded if they were duplicates or if they did not meet the eligibility criteria, for example conference papers, papers on augmented reality (AR) or full-scale simulations, or articles outside the context of STEM in higher education. In the second step, a corpus of studies that was assessed as relevant or possibly relevant (*n* = 85) by the second author was screened by the first author. After this round of screening 35 articles remained. In the third and last step of screening, all full texts were read by both the first and second author. After final exclusions 23 articles remained, and the following items were extracted from full texts included in the review: authors, publication year, title, domain, virtual laboratory definition, type of virtual laboratory studied, study aims and research questions, and conclusions (Table 3).

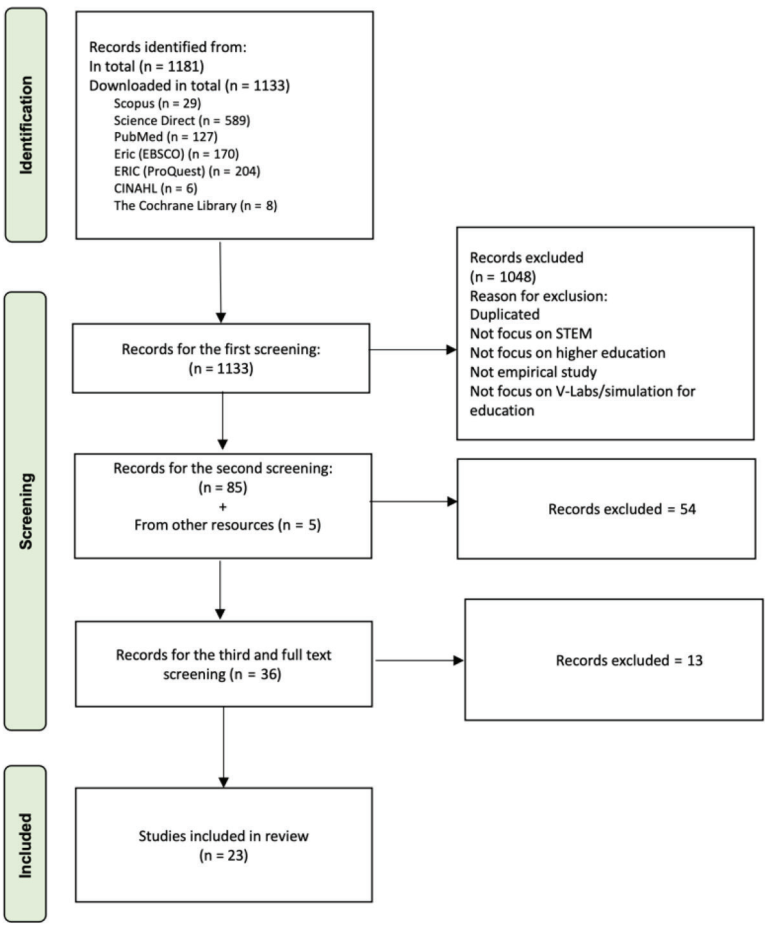


*Figure 1.* PRISMA flow diagram for the scoping review

### *2.4 Limitations*

This scoping review has some limitations that deserve pointing out. First, employing a search string respectively encompassing "Science," "Technology," "Engineering," and "Mathematics" instead of the acronym "STEM" (in pedagogical contexts), could have unearthed additional articles, potentially broadening the scope of included studies. In pedagogical research, the abbreviation STEM has emerged as a widely adopted conceptual label for educational inquiry. In fact, "STEM" is the most used keyword for studies on STEM education (Hsu, 2023). Although there is an extant pedagogical literature from a myriad of branches of respectively science, technology, engineering and mathematics, this study specifically engages with peer-reviewed research that self-describes using the STEM-label. Our choice is motivated by two reasons. First, our choice is theoretically motivated as we see STEM as an *integrated* approach (Martín-Páez et al., 2019). For example, Sanders (2009) conceptualizes STEM as a cohesive entity, integrating all STEM subjects to resolve real-world problems. Similarly, Bybee (2013) supports this integrated perspective, describing STEM education as a spectrum centered on interdisciplinary problem-solving. However, since it can be useful to be more specific about fields of study when exploring STEM in higher education, we differentiate between fields in our overview of included studies (Xie et al., 2015). Second, while we recognize that reliance on the STEM-designation in our search may lead us to miss out on didactic work of importance, it also offers a way to constrain the search and make this scoping review feasible. An exhaustive systematic review, across all disciplines represented by the STEM-acronym, would require an entirely different approach to searching discipline-specific databases. Similarly, opting for "virtual reality," rather of than the widely used term "VR" for our search, might have yielded additional results. A second caveat is that by exclusively considering peer-reviewed journal articles, there is a possibility that we have missed out on relevant and valuable research in the form of unpublished theses, conference proceedings, technical reports, and additional grey literature.

### *2.5 Identifying themes and narratively synthesizing the literature*

Different inductive techniques are used to analyze and synthesize research when conducting a literature review (Kaster et al., 2012; Tricco et al., 2016b). When compiling results from qualitative studies, *thematic analysis* offers a widely used method for identifying and analyzing main themes and prominent ideas in a corpus of research articles. The method involves careful reading of each article to identify and code key themes (units of meaning), and then grouping the related themes together in more abstract categories to create a higher-level summary of salient issues in the literature, based on the researcher's interest. A related approach is *narrative synthesis*, which was adopted here. In reviews, this technique is used to organize and summarize findings from several research articles into a coherent and logical account based on the principle of juxtaposition of different studies, rather than conventional coding of smaller units of meaning. Researchers adopting the principles of narrative synthesis will typically organize findings from each article in a series of interconnected themes or ideas, and construct a comprehensive narrative of the existing research field. One difference between these approaches has to do with the level of abstraction, and the practical details of how abstractions are made. Thematic analysis relies on coding smaller segments of text and then building a catalogue of related themes (higher-level abstractions usually labelled with short titles that capture their gist). Narrative synthesis, on the other hand, begins with units of analysis that are slightly more abstract, and then draws out central concepts in a body of research for theoretical interpretation.

For our narrative synthesis, the 23 articles in question were read critically, considering our two research questions. Information about the type of virtual laboratory being described, definitions, aims and research questions, methods, and conclusions were entered into a spreadsheet extraction table. Our question of how instructional theories inform the literature on virtual laboratories in STEM higher education is principally a metatheoretical issue. Because such conceptual logics are often latent in scientific writings, often requiring higher-level interpretations to identify, we found coding, labelling, and sorting of small text segments less conducive for identifying how instructional theories inform studies on virtual laboratories. Rather, the task of answering this question require a more open-ended, hermeneutically interactive approach, in line with established practices for document studies (Krippendorff, 2018, p. 268): identifying theoretical presuppositions in literature requires an interactive approach where analytical categories are not fixed in advance, but emerge by "actively interrogating" the research papers in question. Such a procedure is broadly hermeneutical because the analytical result emerges iteratively, through a growing understanding of the research literature and how individual contributions relate to one another. This required both close readings of how theory, models and concepts inform individual studies, complemented by a wider metatheoretical reading across the corpus of studies. Results from our narrative synthesis are presented below, in section 3.

## 3 Results

Our search identified 23 journal articles published between 2013 and 2023 within Science ($n$ = 14), Engineering ($n$ = 5) and Technology ($n$ = 4). While desktop and online simulations are the most common platforms for virtual laboratories in our corpus of studies between 2013 and 2019, there is an increase in investigations of virtual laboratories in VR from 2019 and onwards ($n$ = 7). In the sections below, we offer a narrative synthesis of how virtual laboratories are conceptualized in STEM higher education, and the instructional theories, principles and presuppositions that inform the literature on virtual laboratories in STEM.

### *3.1 Conceptions of virtual laboratories in the literature*

We find no commonly shared definition of virtual laboratories in our corpus of included studies. There are, however, some common characteristics between different definitions in the literature, emphasizing aspects of functionality and interactivity, as well as experiential aspects of interacting with and through virtual technologies. We elaborate on these different aspects in the sections that follow.

### *3.1.1. Functional properties of virtual laboratories*

In our corpus, functional dimensions are mostly highlighted for remote laboratories and desktop-based interfaces, as can be seen in the following examples. In Grodotzki et al. (2018, p. 1352), virtual laboratories are described as "providing the students free and convenient access to the laboratory equipment over the internet, incorporating the tele-operative testing cell into lectures and homework helps to link theory with practice." Makransky and Petersen (2019), on the other hand, highlight the ways one can interact with desktop virtual laboratories, by outlining a set of computer equipment such as keyboard, mouse, joystick or touch screen, and headphones, rather than the functional properties of such laboratories. A definition that takes both the laboratory functions and the digital space into account can be found in Garcia-Zubia et al. (2017). Here, the authors describe the remote virtual laboratory as a digital space where students use the Internet to control the equipment and devices needed to perform an experiment. Interestingly, Garcia-Zubia et al. (2017) also state that "the Internet essentially functions as students' hands and eyes" (p. 149) in these environments, conceptualizing an intimate relationship between humans and technology where technology ultimately becomes an extension of the human body.

The idea of "technological embodiment" is not limited to this single article. Several articles engage with postmodern ideas that reconceptualize the boundary between the biological and technical, and how the body may constitute a boundary object between nature and culture (Balsamo, 1995). According to Balsamo (1995), the creation of a boundary between nature and culture fulfills various ideological objectives, with its primary function being to ensure an appropriate arrangement of elements and establish a hierarchical power dynamic between the natural and the artificial. Balsamo elaborates further:

> At a basic level, this socially constructed hierarchy functions to reassure a technologically overstimulated imagination that culture/man will prevail in his encounters with nature. The role of the body in this boundary setting process is significant since it becomes the place where anxieties about the "proper order of things" erupt and are eventually ideologically managed. Techno-bodies are healthy, enhanced and fully functional. (Balsamo, 1995, p. 216)

This intimate relationship between humans and technologies can also be found in Holly et al. (2021) in their study on VR. Here, virtual laboratories are described as a space where learners "become part of the simulated environment by interacting with the virtual world" (p. 107). Becoming part of a virtual environment has been said to be the underlying idea of designing VR technologies (Riva, 2008). By providing a three-dimensional graphical environment, and using visual, aural, or haptic devices, VR provides the means for users to "experience the environment as if it were a part of the world" (Riva, 2008, p. 8). Here, we also see the use of the term "experience," a notion that is central for conceptualizing virtual laboratories in the data corpus, and which we now address.

#### *3.1.2. Experiential aspects of virtual laboratories*

In Reeves et al. (2021), intimacy becomes part of the definition. Drawing on Stanney and Cohn (2012), they describe virtual laboratories in VR environments as immersive technology experiences that "emulate a physical laboratory, allowing students to manipulate equipment, while affording intimate and intuitive interactions" (Reeves et al., p. 1). The idea of an immersive and intuitive technology is recurrently emphasized in the literature on VR in our corpus, pointing towards matters of *realism* and *immersion* as central for the experience. For example, Elme et al. (2022, p. 1603) state that immersive virtual reality "allows for the creation of realistic learning environments that engage the user and create a sense of presence and authenticity." Nuanmeesri and Poomhiran (2019) suggest that virtual reality technology has three common features: "interactive, immersive, and imaginative" (p. 29).

The metaphor of immersion is central here. Writing on the immersion principle in multimedia learning, Makransky (2021) explains how immersion refers to the degree to which a system presents a virtual environment in a way that blocks out the outside world. Technological factors such as tracking level, stereoscopic vision, image and sound quality, field of view, and update rate can also affect the level of immersion (Makransky, 2021). An additional feature is the learner's subjective experience of "being there," which can be influenced by the level of immersion. Moreover, Makransky (2021) argues that the principle of immersion in multimedia learning suggests that immersive virtual environments can enhance learning when they incorporate effective instructional design principles. In other words, it is not the immersive media *itself* that improves learning, but rather the instructional methods used within these environments. Similarly, the sense of presence is described as "an affective affordance of learning in immersive learning environments that can motivate learners to engage in deeper learning" (Makransky, 2021, p. 296). Hence, affordances of virtual laboratory technologies and instructional methods are closely connected to theories of learning in the virtual laboratory literature, which is our next topic.

### *3.2 Theoretical underpinnings of virtual laboratory research*

In this review, we identified ten articles that aimed to evaluate the effectiveness of virtual laboratories (August et al., 2025; Chowdhury et al., 2019; Costabile, 2020; Garcia-Zubia et al., 2016; Gutiérrez-Carreón et al., 2020; Sari et al., 2020; Uriel et al., 2020; Viegas et al., 2018; Wilkerson et al., 2018; Wong et al., 2020). Moreover, we found a small corpus of studies ($n = 4$) aimed at developing virtual labs, measuring aspects such as user satisfaction, user experience and perceived learning outcome, in order to inform system design (Grodotzki et al., 2018; Holly et al., 2021; Nuanmeesri & Poomhiran, 2019; Zupanc et al., 2021). However, studies that explicitly adopt a theoretical position, grounding the analysis of virtual laboratories in the conceptual landscape of learning and the learning sciences, are sparse. To better understand conceptual assumptions informing the field, this section highlights a small set of studies that are explicitly informed by theoretical ideas (*n* = 5).

#### *3.2.1. Embodiment and experiential learning*

As we are dealing with a research field that takes an interest in learners' experience of being immersed in virtual worlds and their learning, it is not surprising to find studies informed by theories on embodied cognition and first-person experiences represented in the corpus. Two studies (Johnson-Glenberg & Megowan-Romanowicz, 2017; Reeves et al., 2021) build explicitly on conceptual frameworks that investigate the role of body, multimodality, action, materiality, and environment as critical resources for the learning process. Johnson-Glenberg and Megowan-Romanowicz (2017) describe an experimental study with a mixed design that explores the interplay between text and "game-like multimedia" with movement and gesture in the learning of abstract concepts about the electrical field in physics. They explicitly refer to theories about the role of gesture, and other bodily modalities, in scaffolding cognitive processes, and use these ideas to draw out implications for instructional design in science education. Building on these theories, their experimental design (across four different conditions) manipulates variables like the level of embodiment, the level of active generativity (in contrast to passive viewing), and the role of story narrative. Using a qualitative design, Reeves et al. (2021) adopt an approach called "phenomenography" (Marton, 1981) to explore learning processes in a VR-lab from the students' perspective. In contrast to the more theoretical aims of phenomenological philosophy, phenomenography offers an empirical approach to document and interpret learning through first-person experiences, with a particular emphasis on the relationships between first-person experiences and the study environment. Here, this method is used to explore first-person views on various affordances of VR-based learning in undergraduate chemistry education. For instance, by adopting the phenomenographic perspective, the authors' document reports on how VR-labs can both constrain and enhance learning opportunities for students. The authors also use the framework to identify and explore dimensions like time use, the sense of isolation in VR, in addition to student expectations towards VR-environments (in contrast to more traditional laboratory-based learning environments).

#### *3.2.2. Social cognitivist theories*

Our review includes a small corpus of studies (*n* = 3) that aim to measure *self-efficacy* in relation to virtual labs (Makransky & Petersen, 2019; Makransky et al., 2016; Wu et al., 2020). Self-efficacy theory was developed by Albert Bandura and based on his broader *social cognitive theory* (Bandura, 1977, 1986, 1997). According to Bandura, self-efficacy refers to one's belief in the ability to accomplish a particular task. Moreover, self-efficacy plays a significant role in learning, as students with higher self-efficacy are more likely to engage in challenging tasks, persist in the face of obstacles, and achieve their goals. Overall, self-efficacy focuses on how an individual's belief in their ability to perform a task can affect their thoughts, emotions, and behaviors. In this way, self-efficacy is closely tied to student motivation, performance, and self-control (Bandura, 1977, 1986, 1997).

In their study of virtual laboratories in microbiology, Makransky et al. (2016) found that the use of virtual laboratories leads to significant gains in student knowledge as well as self-efficacy when used in *combination* with physical teaching laboratories. Moreover, the combination of different modalities may increase students' intrinsic motivation. In a study that follows, Makransky and Petersen (2019) show that students who feel a high level of *presence* during virtual lab activities report larger increases in intrinsic motivation and self-efficacy, which they argue ultimately influences how much they learn. In previous research, the notion of presence has been explained as "the experience or feeling of being present in a mediated environment, rather than the immediate physical environment wherein one is currently bodily present (Makransky et al., 2017, p. 276). Makransky and Petersen's (2019) findings also support the idea that immersion is crucial for learning in virtual environments. In line with these findings, Wu et al. (2020) explored virtual reality with the use of head mounted displays and found that a sense of presence seems to correlate with self-efficacy. The authors, however, emphasize that their findings should be used with precaution, since the head mounted displays also appeared to increase cognitive workload and induce feelings of simulator sickness.[2] Offering a prudent conclusion, they suggest virtual laboratories using immersive technologies such as head mounted displays should be seen as "a promising complement to the traditional way of learning disciplinary problem solving" (Wu et al., 2020, p. 49).

### *3.2.3. Constructivist theory*

Constructivist learning theories have a long history tracing back to the early 20th century and the works of scholars like Jean Piaget and Lev Vygotsky (for an overview, see: DeVries, 2000; Pass, 2004; von Glasersfeld, 2012). In the 1960s and 1970s, a group of educational researchers led by Jerome Bruner began to apply constructivist principles to education, developing a range of perspectives under the label of *social constructivism* (Rannikmäe et al., 2020). Constructivist approaches give weight to the importance of active learning, discovery-based learning and problem-solving in the classroom. Furthermore, they emphasize the significance of paying attention to the processes involved in learning, rather than focusing solely on outcomes. Constructivist learning

[2] Simulator sickness is a form of motion sickness that can happen in virtual environments due to discrepancies between the simulated motion and the user's perception or expectation of motion.

theories have continued to evolve and influence educational practices and have arguably become dominant in educational discourse (e.g., Fox, 2001; O'Connor, 2022). Despite the influence of constructivist theories in the learning sciences, this review found few studies that explicitly adopt a constructivist approach. One exception is Han et al. (2021). In a study on virtual labs for learning computing security and forensics Han et al. (2021) take an explicit theoretical stance, arguing that effective learning in virtual activities requires active engagement with hands-on exercises and activities, putting emphasis on *learning by doing*, and *learning by exploring*, with references to Vygotsky and Piaget. Constructivism, according to Han et al. (2021), emphasizes the need to represent reality and knowledge in multiple ways, and to think deeply about experiences in order to learn from them. To support learning, authentic tasks should be used in an environment that is relevant and meaningful to learners, creating a learning environment that is conducive to understanding and mastering the course material (Han et al., 2021). An important element of research will be to compare not just outcomes, but rather the nature of engagement that emerges in learning situations in terms of how students act, communicate with each other, collaborate in problem-solving and in manipulating the virtual environment. The quality of the interaction is a central matter in this perspective.

## 4 Conclusions and discussion

In this study, a scoping review was conducted to explore how virtual laboratories are conceptualized and theorized in literature on STEM higher education, aiming to uncover the underlying ideas, principles, and assumptions that shape and support the study of virtual laboratories in STEM research. In a previous review, Reeves and Crippen (2021) argued that there is a lack of consistent definitions of virtual laboratories. We note a similar tendency in this review, as there is a striking lack of definitions shared between articles. Likewise, there are articles included in our review that seem to lack a definition of virtual laboratories in the text (Chowdhury et al., 2019; Costabile, 2020; Wu et al., 2020). Reeves and Crippen (2021) present the following useful definition of virtual laboratories:

> Virtual laboratories (v-labs) are technology-mediated experiences in either two- or three-dimensions that situate the student as being in an emulation of the physical laboratory with the capacity to manipulate virtual equipment and materials via the keyboard and/or handheld controllers. (Reeves & Crippen, 2021, p. 16)

Their definition involves several dimensions that are common when describing virtual laboratories. On the one hand, a virtual laboratory should mimic some of the *functional* properties of a teaching laboratory in terms of equipment and materials, and moreover, to do so in an *interactive* way so that the user can manipulate equipment and materials (Diwakar et al., 2023; Garcia-Zubia et al., 2016; Grodotzki et al., 2018; Gutiérrez-Carreón et al., 2020; Makransky & Petersen, 2019; Zupanc et al., 2021). On the other hand, a virtual laboratory in VR should provide an *experience* like being in a teaching laboratory (Elme et al., 2022; Holly et al., 2021; Nuanmeesri & Poomhiran 2019; Uriel et al., 2020; Wilkerson et al., 2022).

Reeves and Crippen's review from 2021 found that nearly half of the articles included in their review lacked a theoretical perspective on learning. Instead, Reeves and Crippens (2020) found a field of research primarily occupied with instrumental evaluations of the effectiveness of virtual laboratories. Similarly, most of the research included in this review focuses primarily on assessments of virtual laboratories to determine either the effectiveness of new technologies in STEM contexts ($n$ = 10), or to inform the design and evaluation of virtual laboratories ($n$ = 4). Only a handful of studies ($n$ = 5) explicitly conceptualizes this work with reference to theories of learning. With the caveat that our sample is small, three theoretical frameworks inform the included studies : (1) *embodiment and experiential learning*, (2) *social cognitivist theories*, and (3) *constructivist theory*. While these theories are not mutually exclusive, we found no attempts at theoretical integration in the literature on virtual labs in STEM.

While we found few studies that explicitly adopt a theoretical framework to inform their design and interpret results, our synthesis reveals a research area dominated by (quasi) experimental designs, mostly aiming to measure effects of using virtual laboratories either through randomized trials or through pre-and posttest questionnaires. Hence, these findings stand in contrast to those of Reeves and Crippens (2021), who identified diversity in research methods. We find the studies in our sample to primarily be associated with STEM-traditions that emphasize the importance of observable behavior and quantifiable outcomes in education. In such cases, measuring the effects of an intervention helps determine whether desired changes in behavior, knowledge, skills, or attitudes are occurring due to the intervention (e.g., Cook et al. 2002). We should also point out that studies aiming to measure various effects of virtual laboratories in STEM education always come with theoretical and conceptual baggage, even if that luggage remains undeclared. Such ideas are associated with legacy traditions in the learning sciences like behaviorism and cognitivism, which remain influential in STEM-discourse about learning through virtual labs. Notably for a field devoted to studying the effects of implementing virtual laboratories in STEM, the descriptive characteristics of "what happens" in the learning situation (Rozin, 2009) is largely ignored as an object of inquiry. Consequentially, our scoping review found few studies ($n$ = 2) that explore the use of virtual laboratories in everyday teaching and learning in STEM higher education, or that focus on the situated learning practices that these resources generate through ethnographic methods or video-based studies. Consequently, the everyday educational practices at work in virtual labs are largely black-boxed in STEM higher education.

The absence of descriptive and qualitative research exploring everyday educational practices using virtual laboratories in naturalistic contexts suggests several practical consequences and areas for further investigation. Adopting a descriptive and qualitative research agenda can provide insights into how teachers and students interact with virtual laboratories in their everyday educational practice. Understanding these interactions can help in refining and improving the design of virtual laboratory technologies to better align with pedagogical goals. Moreover, by studying educational practices involving virtual laboratories, educators can be better equipped with strategies and best practices to better integrate these tools into their teaching as well as into the curriculum. By showing not only *if* virtual laboratories can be an effective means of training, insights into their use can also highlight questions related to *how* to make effective use of virtual laboratories in training, as well as *why* they need to be used and integrated in curricula in certain ways. Ideally, such evidence-based educational practices should influence policymaking in education. However, this review shows that there is a need for more in-depth empirical studies on everyday teaching and learning practices using virtual laboratories, and the conditions under which students develop their knowledge through these tools, in order to productively inform future policymaking in this growing and important field.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Author contribution**

Author 1: conceptualization, investigation, methodology, formal analysis, writing-original draft, supervision, funding acquisition
Author 2: data curation, investigation, methodology
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