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Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design

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ABSTRACT

Practical laboratory courses are an essential part of chemistry education. However, they can be costly and time-consuming. They also require physical presence of the teacher and students and access to well-equipped laboratories, which can be hindered due to equipment cost or a pandemic lockdown. Virtual chemical laboratories are digital tools that become very useful in these situations, but what research has been done on these tools and what elements are important in terms of technology and instructional design? This systematic literature review presents an extensive overview of previous research and addresses the different types of technology and instructional design elements. Results of this study show that virtual labs can be more effective than passive teaching methods (e.g., lecture, text and video), but show equal or greater effectiveness compared to hands-on laboratory. Better results are shown when virtual labs and traditional methods are combined. Most of the included studies use 3D Desktop technology, while immersive VR technology is trending in the last few years. This review also identified instructional design elements used in context of virtual chemical labs, for example, inquiry-based learning, modality, instructional scaffolding. Virtual laboratories can be used as an effective complementary tool or temperate alternative to real hands-on laboratory, but future research should put more emphasis in investigating skill-based learning outcomes using immersive VR and NUI technologies and in considering instructional design in virtual chemical laboratories.

1. Introduction

Laboratory work is often seen as an essential part of chemistry education. Reid and Shah presented four important skills that students acquire during practical laboratory sessions [76]: (1) skills related to learning chemistry, (2) practical skills, (3) scientific skills, and (4) general skills. Seery further elaborated that laboratory work is distinct from the rest of the curriculum in a way that a laboratory is "a complex learning environment, whereby students need to draw together constituent skills, including learning the requisite practical skills, and knowledge, and applying them to a scientific task" [79]. He stated that the laboratory is "the place to learn how to do chemistry". However, physical laboratory sessions are labor- and time-intensive for the personnel involved and the laboratory infrastructure is highly expensive [17,76]. So making these practical sessions available is sometimes a challenging task, especially during a pandemic lockdown when these facilities are not accessible. Online digital tools, such as videoconferencing applications, e-learning platforms and online videos, have been used as alternative to teach the chemical theory behind lab experiments, but a major challenge still exists to adapt practical exercises.

Virtual laboratories are one of the digital tools that can be used to provide distance learning for laboratory sessions. These virtual labs are computer-simulated learning environments that can range from simple 2D visualisations of laboratory experiments to advanced 3D simulations that try to replicate real laboratory environments [50]. With recent virtual reality (VR) technology, it is even possible to be fully immersed in the virtual laboratory environment performing realistic laboratory handling [38,52]. Some benefits that virtual laboratories can offer, compared to traditional hands-on laboratories are [3,5,32]: reduced cost, greater accessibility, time-saving, safe environments, and flexibility of self-regulated learning. However, depending on how the virtual lab is used, absence of other students or tutors, and lack of real-life feel of a laboratory may present drawbacks of these virtual applications

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[58].

Due to distance learning becoming more popular nowadays, one can expect more varieties of virtual laboratories in the near-future. However, designing and developing such a complex virtual learning environment is not always that easy. It often requires a multidisciplinary team with different levels of expertise (e.g., computer scientists, educational technologists and chemistry teachers) in order to create an effective learning experience [65]. Furthermore, research has shown that the technological aspect is not the only contributing factor for the design of effective virtual learning environments. In some cases, the technological design can even be inhibiting for cognitive learning processes if not optimally designed [61,64]. A rigorous instructional design is required that utilises well-established learning theories and instructional support in order to optimize the effectiveness of the virtual laboratory experience.

2. Related work

Research on virtual laboratories is not a new topic. In fact, several reviews have been published comparing virtual and remote laboratories to traditional hands-on laboratories [18,32,58,59]. However, these reviews include laboratory practices of many other disciplines (e.g., biology, physics, engineering sciences) and few virtual laboratories in chemistry are mentioned. Only four other reviews were found that discuss virtual chemical laboratories more in depth [3,15,82,85].

Tatli and Ayas published the first review on the subject and examined 13 papers reporting virtual chemical laboratories that are based on a constructivist learning approach in order to analyze their advantages and disadvantages [85]. They investigated the purpose of the studies, sample size, data collection tools and study results. This study concluded that these labs allow students to focus on the process rather than on the equipment, promote active participation with little to no time waste, and allow experiments to be repeated in a safe environment. The major drawback was that students using virtual laboratories could not feel, smell or touch as in a real laboratory.

Sypsas and Kalles analysed 29 peer review articles of virtual laboratories in the domains of biology, biotechnology and chemistry [82]. They were focused on its effectiveness as supplementary tool and the educational approaches that are used. This study concluded that virtual laboratories show similar or better results than conventional methods for secondary education and that they are most effective when it is combined with real laboratory for post-secondary education. Blended learning and inquiry learning were the most used educational approaches. They also mention that their review might have excluded a lot of research papers, and they encourage to update such reviews frequently as technological advancements improve rapidly.

Bellou et al. reviewed 43 studies of digital learning technologies in primary and secondary chemistry education [15]. They primarily looked into the learning technologies, pedagogical approaches, research methods and learning outcomes of the studies. From the technical approaches they have analysed, seven of them were virtual labs, whereas the most used technological approaches were multimedia and simulations. Their findings of their review suggest that most studies involve secondary education; cover mostly particulate nature of matter as topic; and have adopted mostly constructivist learning theories. Furthermore, the research method of most studies assessed the student’s knowledge following an experimental and quasi-experimental design with a majority reporting positive learning outcomes. However, the authors have remarked that proceedings of conferences and book chapters were not included and suggested a more systematic effort with more meta-analyses of empirical studies.

Ali and Ullah conducted a literature review collecting 42 different virtual chemistry laboratories. They proposed a classification of the type of graphical interfaces used in these virtual laboratories [3]. The authors made a distinction between 2D, 3D and video metaphor virtual chemistry laboratory with a further separation of offline and online virtual labs. From this collection, a comparison was made between 2D and 3D virtual chemistry laboratories to reveal their similarities and differences. Ali and Ullah noted that 2D virtual labs lack realism and provide low immersion compared with labs that use 3D graphical interface. Furthermore, they have discovered that most of the virtual labs did not provide any guidance on the procedure of an experiment.

Our work is distinct from these literature reviews. Firstly, because this study includes novel virtual technologies, such as immersive virtual reality (VR). Ali and Ullah briefly mentioned this type of technology, but it was classified under 3D virtual laboratories [3]. Secondly, this study provides a holistic overview of previously used virtual chemical laboratories in research literature. This means that it also includes conference proceedings and virtual laboratories at university level, which were not included in the studies of Sypsas [82] and Bellou et al. [15], respectively. Thirdly, this study considers features of instructional design that were taken as the basis for the design of the virtual chemical laboratories.

3. Research goal and research questions

The main goal of this systematic literature review is to provide an extensive overview of previous research on virtual laboratories in chemistry education. We investigate three main characteristics: research methods, technology and instructional design. Therefore, the following main research questions are stated for this study:

> RQ 1: What are the main research purposes, evaluation methods and learning outcomes in studies on using virtual chemistry laboratories for educational purposes?
> RQ 2: Which technologies have been used for virtual chemical laboratories and what is the current trend?
> RQ 3: What learning theories and instructional design features have been applied in virtual chemical laboratories?

Eventually, this review could contribute as an aid for teachers and educational developers to select effective solutions for the distance learning of chemical laboratory practices.

4. Methodology

In order to conduct this systematic literature review, we have followed PRISMA’s principles and guidelines [66]. These guidelines help researchers to conduct a transparent and complete reporting of systemic literature reviews. It requires the author to specify the search strategy, eligibility criteria, selection process and data collection process.

4.1. Database and search keywords

The first step of this systematic literature review is the literature search in an online the database. As such, we conducted a search in November 2020 using Web of Science as scientific database. We used a combination of search terms to find publications about virtual applications or games that considered chemical laboratory, chemical experiment or laboratory safety instructions:

- (virtual OR game) AND (chemical OR chemistry) AND (laboratory OR lab);
- (virtual OR game) AND (“chemical experiment” OR “chemistry experiment”);
- (virtual OR game) AND (“lab safety” OR “laboratory safety”).

These search terms should be found in the title, abstract or list of keywords of publications between 2000 and 2020. This search yielded 806 records after removing duplicates. Additionally, 8 records were added by manually searching on Google Scholar and by examining the bibliography of the publications. Eventually, a total of 814 records remained to be screened.

4.2. Inclusion and exclusion criteria

The next step of our study is dedicated to selecting the relevant articles to be included for this review by screening the title and abstract of each record. For this selection, we used a number of inclusion and exclusion criteria in order to filter out the irrelevant publications (Table 1). This title and abstract screening resulted in 113 valid publications and 701 records were removed. These selected publications were then subjected to further screening of their full text. We filtered out publications of virtual laboratories that did not contain a chemical experiment or a representation of a virtual laboratory environment. For example, publications where a virtual application was used to only visualize molecule structures [33] were excluded. Another criterium is that the type of display technology (e.g., 2D, 3D or immersive VR) should be described in the text or represented in the images of the publication. After screening of these texts, a total of 76 publications remained that are included in this literature review.

4.3. Data analysis and coding

In this last step, we analysed the 76 included publications by coding the relevant information that is appropriate to our research questions onto a spreadsheet. These variables were then classified in distinct categories introduced in this section. Appendix A shows a table of this classification with clear description of each category. The full coding scheme of each publication with their identification number can be found in Appendix B.

4.3.1. Research purposes

The research purpose of the publications that report the use of virtual chemical laboratories can be classified into three main categories: comparative, evaluative and technical.

Comparative studies investigate two or more intervention groups either comparing the media or the design of the virtual laboratory. Following the definitions of Mayer et al., the former is called media comparison while the latter is called value-added research [64]. In media comparison research, the learning outcome of an experimental group using a virtual chemical laboratory application is compared with a control group that had the same learning content but with a different educational medium. For example, the study of Tarng et al. compared the experimental group performing experiments in the virtual laboratory with a control group performing experiments in a real hands-on laboratory [83]. Furthermore, lectures, videos, text and demonstrations were grouped together as 'passive media' because these media do not require active participation from the participant, unlike virtual and hands-on laboratories. In value-added studies, a basic version of a virtual laboratory application is tested with a control group, while the intervention group uses the same basic version but with one design feature added or changed. For example, the study of Ullah et al. used a virtual lab with procedural guidance and a virtual lab without procedural guidance [87]. The learning outcomes of both versions are then compared to each other which allows the investigation of the effectiveness of a specific design principle.

Evaluative studies only consider the virtual laboratory group in order to evaluate a particular outcome. Affective reactions, such as attitude, satisfaction or self-efficacy of the participant can be measured in order to evaluate the user experience and usability of the system. In this case, we have grouped these publications under 'user study'. Other studies have investigated the performance of using the virtual laboratory without a control group only to evaluate the performance gain or assessment method. This category is called 'performance assessment'. Evaluative studies with other purposes, for example a correlation study [78], are identified with 'Other'.

Technical studies do not perform any measurements to evaluate the virtual laboratory, but rather describe its design and development. Although no measurable results are presented in these publications, they are still valuable for this review as they describe the technical advances that has been implemented in virtual chemical laboratories.

4.3.2. Evaluation methods

Evaluation methods are collected and categorised from studies who have performed measurements (i.e. comparative and evaluative studies). These include quantitative and qualitative methods, similar to Brinson et al. [18]: test, lab practical, real-time assessment, school grade, questionnaire, interview and observation. Lab practical refers to hands-on lab experiments to assess laboratory skills, while real-time assessment refers to collecting data within the virtual lab application that are retrievable using log files.

4.3.3. Learning outcomes

The learning outcomes that are measured in the reviewed studies are categorised in three domains according to Kraiger et al. [56]: cognitive, affective and skill-based. Cognitive domain refers to the cognition of the participant which includes declarative knowledge (knowledge of facts and concepts), procedural knowledge (knowledge on how to perform a task) and conditional knowledge (knowledge on how and when to apply principles to solve problems) [8]. Affective domain refers to personal reaction of the participant which includes attitude, usability and self-efficacy. Skill-based domain refers to technical or practical skills of the participant, for example, practical laboratory skills.

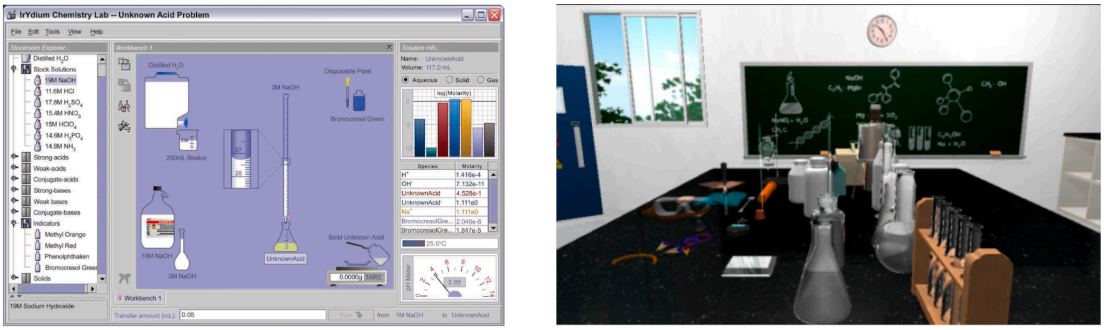
4.3.4. Technology type

A distinction is made between display technologies and natural user interfaces (NUIs). Display technologies are graphical characteristics using a certain display device and are categorised in 3 different types: 2D desktop, 3D desktop and immersive VR. Studies belonging to the 2D desktop category describe virtual chemical laboratories that are displayed on a desktop monitor display and feature a 2D representation of the environment and objects. In the 3D desktop category, virtual chemical laboratories are displayed on a desktop monitor display as well, but are 3D in nature, meaning that the virtual environment and objects have a depth and are built from 3D geometries. Studies included in the immersive VR category describe the use of modern VR devices where the user is fully immersed in the virtual environment without visual interaction with anything else from the real world other than the display. This mainly concerns the use of VR head-mounted displays (HMDs). These VR devices are also able to display a different image per eye, allowing a 3D stereoscopic view that results in the perception of real depth. Fig. 1 shows examples of these types of technologies.

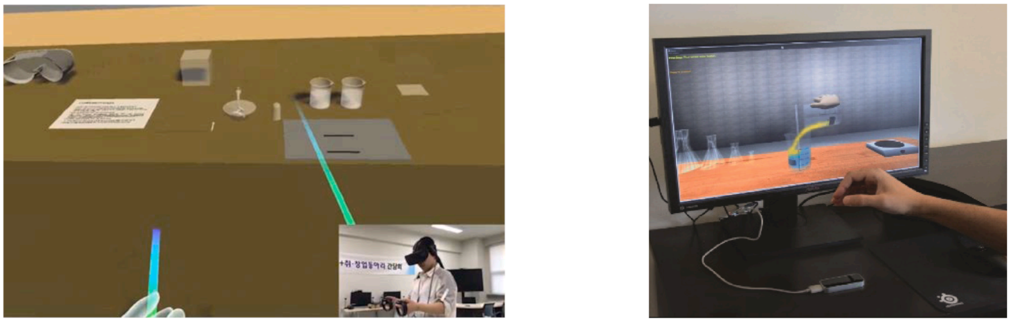
A further distinction can be made whether the authors have used special input devices as NUIs in addition to a display technology. These NUIs use human movement or gestures as input to control the system "in such way that the user is not aware of the existence of an interface" [47]. These include devices that provide advanced tracking capabilities, such as movement/rotational tracking, spatial tracking, and tracking of hand

Table 1
A list of inclusion and exclusion criteria used to select relevant articles from the search results.

Inclusion	Exclusion
Journals and conference proceedings	Reviews, abstracts and non-peer reviewed publications
Virtual laboratories used for chemistry education	Publications with full text that is not accessible
Contains chemical laboratory practices or laboratory safety	Virtual applications that is only used to teach chemical concepts (e.g., molecule visualization, periodic table)
Uses 2D, 3D graphical interfaces or immersive virtual reality devices	Virtual lab applications that requires the real environment (e.g., augmented reality)
Publications must be in English	Publications that are not in English



2D Desktop (Yaron et al., 2010) 3D Desktop (Su & Cheng, 2019)



Immersive Virtual Reality (Duan et al., 2020) Natural User Interface (Aldosari & Marocco, 2016)

Fig. 1. Examples of types of technology used in virtual chemical laboratories in the reviewed studies: 2D Desktop [96], 3D Desktop [81], Immersive Virtual Reality [29] and Natural User Interface [1].

gestures or body gestures.

4.3.5. Instructional design

The instructional design of the virtual chemical laboratories is analysed by identifying the learning theory and instructional support elements that were used in these publications. This was done by examining which learning theory has been applied using the terms derived from the collection of Kebritchi and Hirumi [51]. Likewise, for examining instructional support elements, the list of Wouters and Oostendorp was used to identify the terms [94]. Publication with no learning theory or no instructional support indicated, were marked with ‘not specified’.

5. Results

This section connects the results of the review inquiry to the three research questions mentioned in Section 3 and is divided into three subsections: research methodology, technology and instructional design.

5.1. Research methodology

5.1.1. Research purposes

Table 2 shows the three categories of research purposes (i.e. comparative, evaluative and technical studies) with the corresponding publications as reference, while Fig. 2 shows the relative distribution of these categories.

We have observed that the majority of the publications could be identified as ‘comparative study’ ($n = 38$, 50%). In this category, most studies have conducted media comparison ($n = 33$) rather than value-added research ($n = 3$), while some studies have combined both ($n = 2$).

The second most common research purpose is the ‘evaluative study’ category ($n = 24$, 32%). Most studies ($n = 15$) used this approach to conduct a user study by examining the affective reactions of the participants. Five other studies ($n = 5$) have investigated the performance of using the virtual laboratory without a control group in order to evaluate the performance gain or real-time assessment method. Some studies ($n = 3$) combined both user study and performance assessment. Also, one other study used their virtual chemical laboratory for a correlation study [78].

Table 2
Classification of categories of research purposes.

Research purpose	Sub-category	n	References (ID nr. from Appendix B)
Comparative study	Media comparison	35	49, 17, 14, 33, 53, 63, 11, 30, 64, 5, 40, 68, 1, 34, 35, 62, 18, 57, 10, 31, 60, 61, 70, 24, 32, 36, 45, 69, 47, 39, 65, 67, 25, 38, 56
	Value-added research	5	39, 65, 13, 75, 48
Evaluative study	User study	18	58, 19, 73, 76, 22, 41, 4, 7, 55, 6, 54, 15, 20, 52, 2, 23, 50, 71
	Performance assessment	8	72, 9, 16, 8, 58, 19, 73, 26
	Other	1	59
Technical study		14	12, 28, 51, 27, 74, 3, 37, 42, 29, 43, 46, 66, 21, 44

With N = number of studies.

Publications belonging to the ‘technical study’ category are found to be the least common among the two other categories ($n = 14$, 18%). These studies are intended to introduce the design and technology of the virtual chemical laboratory and to describe the development of such applications.

5.1.2. Evaluation methods

To evaluate the effectiveness of virtual chemical laboratories, a mix of quantitative and qualitative evaluation methods has been used for measuring cognitive, affective and/or skill-based learning outcomes. As seen from Fig. 3, there is a notable difference in the use of these methods between comparative and evaluative studies.

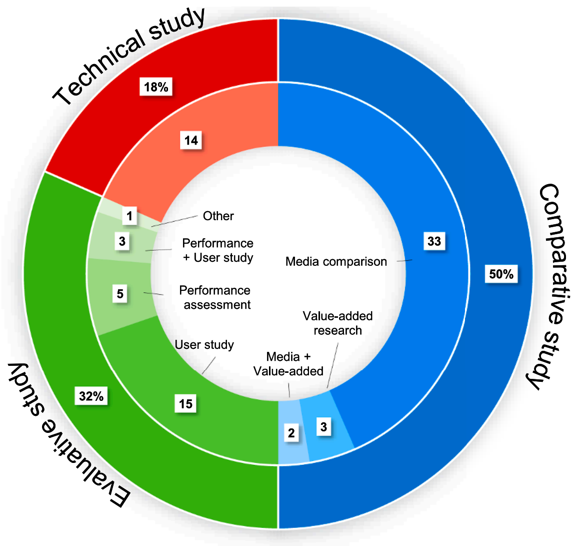


Fig. 2. Pie chart presenting the distribution of publications according to their research purpose. Corresponding references are listed in Table 2.

Tests are the most frequently used evaluation methods for comparative studies (n = 32, 84%), while questionnaires are the most used methods for evaluative studies (n = 21, 88%). Comparative studies also seem to have used qualitative evaluation methods to measure affective outcomes of participants, such as questionnaires (n = 23, 61%), interviews (n = 8, 21%) and observations (n = 7, 18%). We also observe that lab practicals were applied in comparative studies (n = 9, 24%) and not in evaluative studies, while real-time assessments were used more in evaluative studies (n = 6, 25%) than in comparative studies (n = 2, 5%).

5.1.3. Learning outcomes

When investigating learning outcomes, we observed that most comparative studies measure cognitive learning outcomes (n = 35, 92%), whereas most evaluative studies measure affective outcomes (n = 19, 79%), as seen in Fig. 4. However, affective outcomes of participants are also frequently measured in comparative studies (n = 22, 58%). This is because these studies also evaluate the usability of the virtual laboratory and opinions of the participants besides cognitive and/or skill-based comparison. The least evaluated learning outcome is the skill-based outcome, both for comparative (n = 11, 29%) and evaluative studies (n = 2, 8%). When investigating the sub-categories of these learning outcomes in Table 3, we find that declarative knowledge is the most measured learning outcome in the cognitive domain (n = 34) and usability in the affective domain (n = 31). Studies with 'Other' category investigated items that are not outcomes of learning, such as level of constructivist teaching [84] and user profile [9].

Media comparison. A popular discussion can be noticed within the reviewed studies about how virtual chemical laboratories are compared with traditional teaching methods. For this reason, the majority of the studies have conducted media comparison research. Table 4 shows an overview of the virtual labs (or combination with virtual labs) with the compared medium. Publications in which significantly better results are presented for using virtual labs are identified as 'positive', while publications showing non-significant different results are identified as 'equal'. Publications showing significant results against virtual labs are identified as 'negative'.

Results of these studies show that when compared to passive media, a majority of virtual labs report positive improvement, mainly in declarative and conditional knowledge (n = 11). Some studies (n = 4) reported equal effectiveness in declarative knowledge, but identified better results in conditional knowledge and self-efficacy in favor of virtual labs [42,46,60,92]. When virtual labs are compared to hands-on laboratories, results are mixed. Six studies (n = 6) reported positive improvement for virtual labs mainly in declarative knowledge with a total population of 639 participants, while nine studies (n = 9) observed equal effectiveness including declarative knowledge and skill-based learning outcomes with a total population of 1662 participants. Also for affective learning outcomes, virtual labs are not significantly different from hands-on labs in terms of attitude towards chemistry laboratory (including anxiety, satisfaction), usability and self-efficacy (regarding confidence) of the participants [23,41,91]. Two publications presented worse results in attitude and usability against the virtual lab compared to hands-on laboratory [41,40] and one study reported worse results in declarative and conditional knowledge [75]. However, Hensen et al. have mentioned that the adverse attitude was due to an instructor effect (i.e. inexperienced teacher-assistants) [40]. When this was corrected, they found no significant differences.

In other studies, virtual labs were combined with passive media or hands-on laboratories and were compared with traditional teaching methods alone (only passive media or only hands-on labs). From Table 4 we see that these combinations have mostly positive improvements in terms of declarative and conditional knowledge compared to only

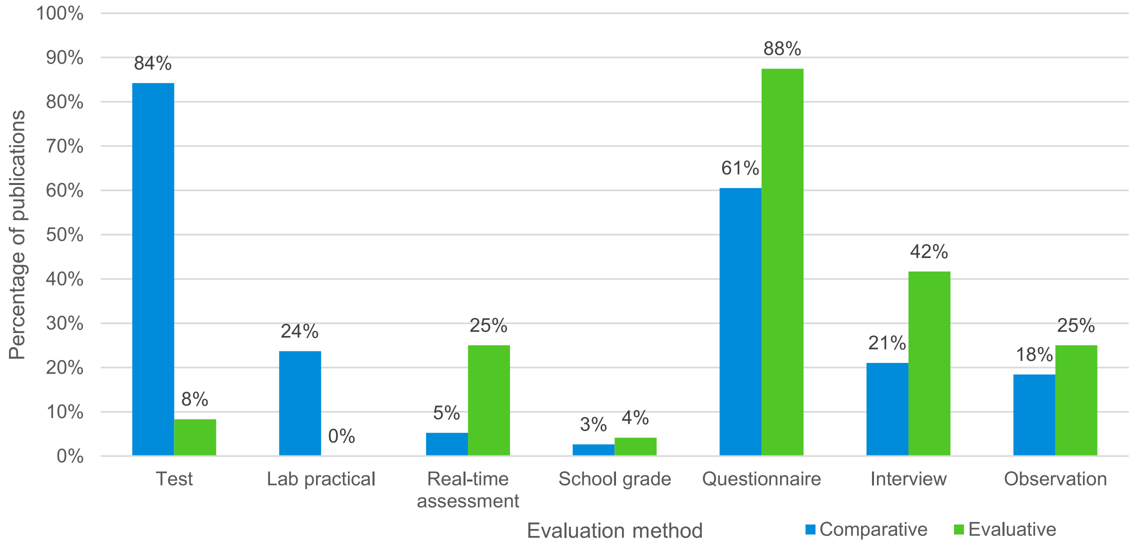


Fig. 3. Bar graph showing the percentage of the evaluation methods used in comparative studies (blue/left bars) and evaluative studies (green/right bars)

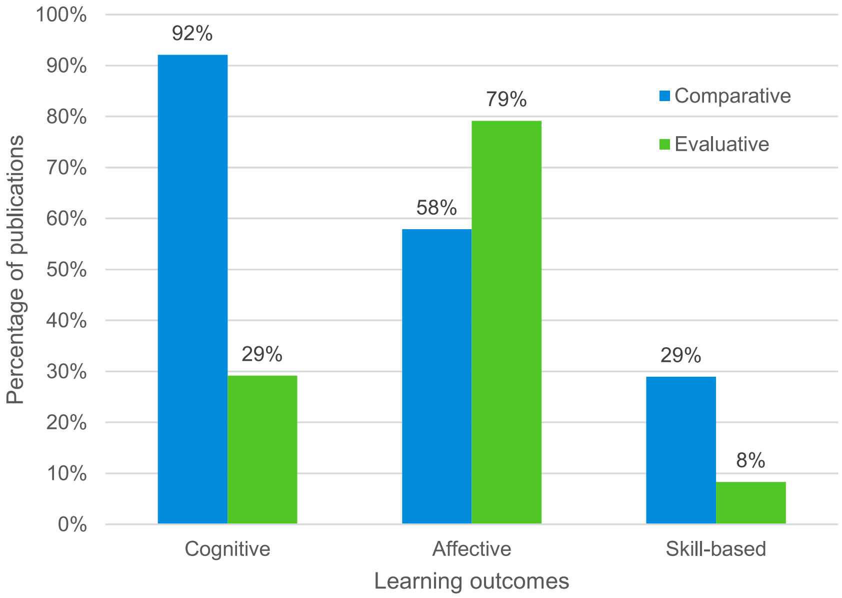


Fig. 4. Bar graph of learning outcome measured in comparative studies (blue/left bars) and evaluative studies (green/right bars).

Table 3
Collection of learning outcomes covered in the reviewed publications.

Learning outcome domain	Sub-category	n	References (ID nr. from Appendix B)
Cognitive domain	Declarative knowledge	34	49, 13, 72, 17, 75, 14, 33, 53, 30, 64, 5, 9, 40, 68, 1, 34, 39, 35, 65, 62, 67, 8, 18, 57, 60, 61, 70, 24, 32, 69, 47, 48, 25, 38, 56
	Procedural knowledge	11	49, 14, 53, 58, 16, 65, 8, 18, 25, 26
	Conditional knowledge	20	49, 72, 13, 33, 59, 11, 40, 34, 39, 35, 67, 70, 32, 36, 47, 48, 25, 26, 38, 56
Affective domain	Attitude	12	17, 14, 22, 4, 67, 10, 31, 52, 32, 69, 53, 25
	Usability	31	71, 72, 13, 53, 41, 5, 58, 76, 54, 55, 65, 6, 7, 19, 62, 67, 57, 15, 20, 60, 73, 2, 23, 50, 17, 31, 40, 39, 52, 68, 69
	Self-efficacy	11	17, 5, 40, 39, 61, 45, 47, 52, 65, 71, 53
	Social presence	1	48
Skill-based domain	Practical laboratory skills	11	49, 53, 30, 5, 68, 19, 57, 73, 69, 47, 25
Other		2	63, 9

With N = number of studies.

Table 4
Outcomes of comparative studies including a virtual lab, passive media and/or hands-on lab training. Indications of the following features are given: dk = declarative knowledge; pk = procedural knowledge; ck = conditional knowledge; sb = skill-based att = attitude; se = self-efficacy; us = usability; *o* = other; *n* = number of publications; *p* = population size.

Compared with	Virtual lab	Passive media	Hands-on lab
Virtual lab	/	Positive ($n = 11$, $p = 1053$) references: 61(dk), 14 (dk,pk), 35(dk,ck), 33 (dk,ck), 5(dk,sb), 11 (ck), 34(ck), 70(ck), 40(ck,se), 47(ck,sb, se), 63(o) Equal ($n = 4$, $p = 630$) references: 47(dk), 40 (dk), 34(dk), 70(dk)	Positive ($n = 6$, $p = 639$) references: 62(dk), 1 (dk), 64(dk), 60(dk), 53(dk,pk,sb), 65(dk, pk,se,sb) Equal ($n = 9$, $p = 1662$) references.: 64(dk), 24 (dk); 30(dk,sb), 57(dk, sb), 68(dk,sb), 53(dk, pk,sb), 67(dk,ck,att, us), 17(dk,att,se), 32 (dk,ck,att) Negative ($n = 3$, $p = 1260$) references: 31(att, us), 32(us), 56(dk,ck)
Virtual lab + hands-on lab	Positive ($n = 1$, $p = 87$) references: 60(dk) Equal ($n = 1$, $p = 141$) references: 1 (dk)	/	Positive ($n = 6$, $p = 3060$) references: 1(dk), 60 (dk), 36(ck), 49(dk,pk, ck,sb), 25(dk,pk,ck, sb), 10(att), 45(se) Equal ($n = 2$, $p = 346$) references: 69(dk,att, sb), 38(dk,ck) Negative ($n = 1$, $p = 1141$) 25(att)
Virtual lab + passive media	Positive ($n = 1$, $p = 1334$) references: 18(dk)	Positive ($n = 2$, $p = 360$) references: 57(dk), 39 (dk,ck,se)	Positive ($n = 2$, $p = 192$) references: 36(ck), 10 (att)

passive media (2 positive) or only hands-on laboratory (5 positive vs 2 equal). For affective learning outcomes (including attitude, usability and self-efficacy), results are somewhat mixed. On one hand, Astuti et al. and Kolil et al. reported positive results in attitude and self-efficacy when virtual labs combined with passive media and hands-on labs are compared with hands-on labs only [10,55]. On the other hand, Winkelmann et al. observed no difference in attitude [89] and Enneking et al. reported that students in the hands-on lab group developed better attitude for laboratory practices than when it is combined with virtual labs [31]. However, when these combined virtual labs are compared with virtual labs only, they seem to be at least as effective in declarative knowledge (2 positive vs 1 equal). Studies with this comparison are uncommon.

User studies and performance assessment. Data have been collected from the reviewed publications that evaluated the affective reactions and opinions of the participants on the virtual chemical laboratory. Results were extracted from questionnaires, interviews and observations of the publications where attitude, usability and self-efficacy were examined and are presented in Table 5.

The affective learning outcomes of the participant's attitude are separated into two types: attitude towards the subject of chemistry and

Table 5
Overview of affective learning outcomes reported in publications that performed user studies and performance assessments of the virtual chemical laboratory applications.

Affective learning outcomes	Sub-category	Positive	Neutral	Negative
Attitude	Attitude towards the subject of chemistry	14, 10, 52, 53, 67, 31, 32	17, 69, 25	
Usability	Satisfaction	17, 4, 7, 71, 76, 65, 6, 19, 62, 60, 73, 2, 23, 69, 31	50, 54	
	Usefulness	17, 53, 68, 4, 7, 52, 71, 13, 41, 5, 76, 55, 65, 6, 19, 62, 57, 15, 20, 60, 73, 2, 23, 50, 40, 39, 31, 32, 69	54	
	Easy to use	53, 4, 7, 68, 71, 5, 58, 76, 65, 6, 62, 57, 20, 60, 2, 31, 32		54
	Time efficiency	68, 7, 67, 71, 72, 41, 76, 6, 40	57, 54	
	Realism/ authenticity	5(NUI(3D)), 62(3D), 20(3D), 2(3D), 23 (immersive VR), 54 (3D)		52(2D), 55(2D)
Self-efficacy	Confidence in laboratory work	52, 71, 47, 65, 40, 39 5, 61, 45	17	
Performance assessment	Knowledge gain	9, 8, 72		
	Log data assessment	16, 58, 73, 19, 26		

system usability. The former refers to a person's feelings and beliefs about chemistry and chemical laboratory work, which includes anxiety, satisfaction, intellectual accessibility, usefulness of lab and interest-feeling [13]. Also scientific attitude [10,20] and open-endedness of lab [72] are added to this category. The system usability refers to the attitude of the participants towards the virtual laboratory application, which includes satisfaction, usefulness of virtual labs, ease of use, time efficiency and realism.

The findings of questionnaires evaluating the usability suggest that participants have overall positive opinions about virtual chemical laboratories. They consider the virtual laboratories to be satisfying, easy to use, useful for learning and take less time than real laboratory work. However, Moozeh et al. noticed that students were not satisfied by using the virtual lab as post-lab exercise after hands-on laboratory session [67]. In the study of Qvist et al., difficulties were found in using the user interface and movement control, which affected the students' satisfaction and opinion on time efficiency [73]. Also, some teachers preferred using the real laboratory over the virtual laboratory due to the lack of real laboratory handling and communication between students and assistants [73]. In terms of realism, participants found the virtual laboratories to be realistic in studies where 3D, NUI or immersive VR technologies were used. However, other studies reported a lack of realism and authenticity for 2D virtual laboratories [70,74].

When examining attitude towards chemistry, studies generally revealed positive outcomes in terms of anxiety, interest, usefulness of lab, scientific attitude and open-endedness of labs. Although some of these studies reported no significantly different or worse results compared to hands-on laboratory, participants still displayed positive to neutral attitude towards chemistry and towards usability of virtual laboratories [31,41,40,91].

Most studies have reported positive influence on self-efficacy of the participant after using virtual chemical laboratory [55,60]. More in particular, virtual labs have increased the participant's confidence in performing laboratory activities and in thinking like a chemist [4,46,47,70,87,93]. One study found that confidence was not significantly different from hands-on laboratory. However, they claim that this is because the participants were self-selected and that confidence possibly was increased to the same level as the group of hands-on laboratory [22].

Evaluative studies that only assessed the performance of the virtual lab group have measured significant knowledge gain by using knowledge tests [7,9] and school grades [93]. Other studies were able to distinguish low performing from high performing learners by measuring data during the virtual experience, such as time, number of steps, number of errors and number of hints used [21,25,36,77,95].

5.2. Technology

5.2.1. Display technologies and natural user interfaces

We identified the type of technology used in the reported virtual chemical laboratory by examining indications of the technology in the text and in the images of the publication. We observed two distinct types of technology used in virtual chemical laboratories as explained in Section 4.3.4: display technology and natural user interface.

Display technologies are used to visually display chemical experiments or the laboratory environment. The majority of publications have reported the use of virtual laboratories with 3D Desktop technology ($n = 37$, 49%), while 2D Desktop is second ($n = 29$, 38%) and immersive VR as third most used ($n = 10$, 13%). Examples of immersive VR HMD devices used in this study are: Oculus Go™, Oculus Rift® and Samsung Gear VR®. However, studies using 2D Destop virtual labs seem to have tested more participants (5994 people) than studies with 3D Desktop (5241 people) or immersive VR (511 people). Table 6 shows the classification of technology types with the corresponding publications as reference, while Fig. 5 presents the distribution of the technology types with total population size of the studies per type.

Natural user interfaces (NUIs) can be characterised as input devices to control the virtual environment of the application. NUIs use tracking sensors in order to precisely capture the movement of the user's body. For instance, NUI devices that track the movement or rotation of the hand by using controllers or using cameras such as a Wii Remote™ or Kinect®. These have been used in 5 publications [4,46,47,87,92]. Devices tracking finger gestures, such as Leap Motion™ controller, have been used in 8 publications [1,2,6,38,45,52,53,95]. Only one publication reported the use of NUI devices tracking the whole human body such as a Kinect® [25]. As NUIs are used in combination with a visual display technology, publications using 3D Desktop have implemented NUIs ($n = 8$) more frequently than publications using 2D Desktop ($n = 4$) and immersive VR ($n = 2$).

5.2.2. Technology trend

In order to identify the current trend of technology use in virtual chemical laboratories, a distribution of technology types is presented per

Table 6
Number of studies using a type of display technology with or without a type of NUI.

Display	n	References	NUI	n	References
2D Desktop	25	49, 33, 53, 30, 1, 34, 35, 18, 57, 60, 45, 13, 59, 16, 8, 22, 7, 55, 15, 52, 50, 74, 26, 38, 56	Movement/ rotational tracking Hand gestures	3 1	40, 39, 70 6
3D Desktop	29	17, 14, 63, 11, 64, 68, 62, 67, 31, 61, 32, 69, 75, 54, 71, 72, 9, 58, 76, 41, 20, 2, 12, 28, 51, 27, 46, 21, 25	Movement/ rotational tracking Hand gestures Body gestures	2 5 1	5, 65 4, 3, 37, 42, 43 19
Immersive VR	8	10, 24, 36, 47, 48, 23, 66, 44	Hand gestures	2	73, 29

With N = number of studies.

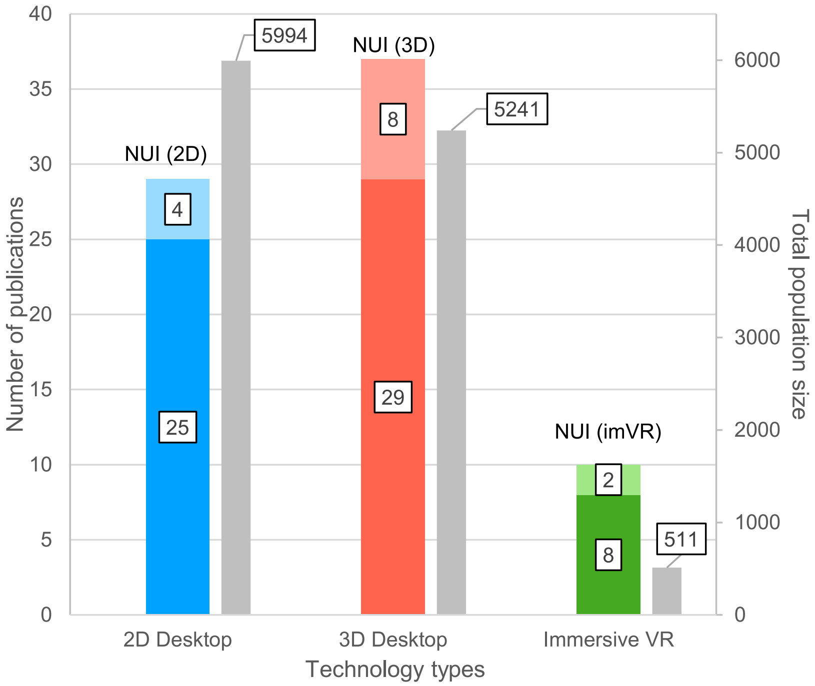


Fig. 5. Number of publications (left bars) and total population size in all studies (right bars) per technology type. A distinction between display technology without and with NUI (bottom versus top color) is made.

year over a time span from 2003 to 2020 in Fig. 6. It shows that research using virtual chemical laboratories with 2D Desktop and 3D Desktop technologies has been prominent throughout the years since the early 2000s with a sharp increase starting from 2012. NUI devices started to be implemented in virtual chemical laboratories from 2014, but have not remained largely present in the last few years. Instead, there has been an increase in the use of immersive technology starting from 2018.

5.3. *Instructional design*

5.3.1. *Learning theories*

The learning theories, that are explicitly indicated in the text or as keyword of the reviewed publications, are extracted and presented in Table 7 with a short description of each theory. Our findings suggest that inquiry-based learning/discovery learning ($n = 7$) and learning-by-doing ($n = 5$) are two of the most used learning theories for virtual chemical laboratories. However, the large majority of the publications ($n = 53$, 70%) have not specified any learning theory.

5.3.2. *Instructional support*

Instructional support elements are also extracted from the reviewed publications and are presented in

Table 8 with the corresponding description. We observed that feedback ($n = 11$), scaffolding/guidance ($n = 8$) and modality ($n = 6$) are the top 3 most frequently used instructional support elements in virtual chemical laboratories. However, similar to learning theories, the large majority of the publications ($n = 55$, 72%) have not specified any instructional support.

Value-added research. In order to evaluate the effectiveness of some of the instructional support elements, a small part of the comparative studies have performed value-added research. Table 9 shows an overview of these comparisons and the achieved results. From these studies, the instructional support principles of modality and spatial contiguity have been confirmed when applied to virtual chemical laboratories. Providing instructions in audio voice is observed to be more effective than textual or video instructions [47] and displaying learning information near the object seems to be more effective than when it is unrelated to its position [97].

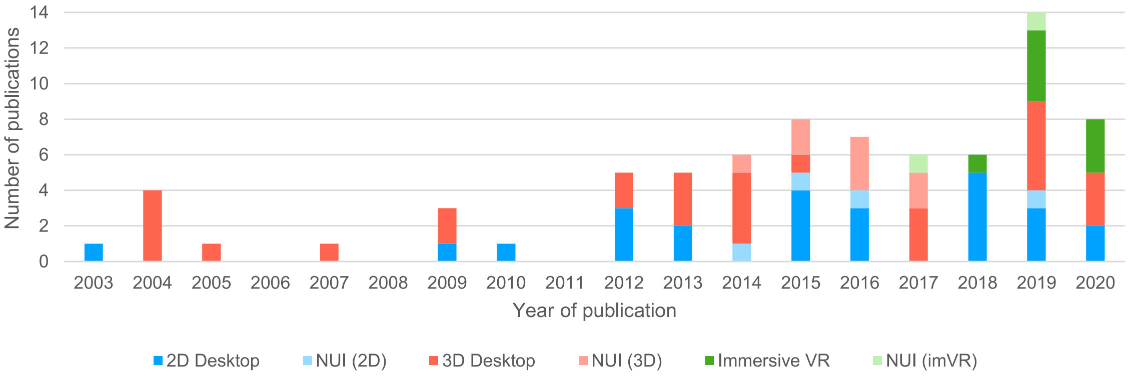


Fig. 6. Distribution of technology types that are reported in the reviewed publications over a time span of 2003 to 2020.

Table 7
Collection of learning theories used in virtual chemical laboratories of the reviewed publications.

Learning theories	Description	n	Ref.
Inquiry-based & discovery based learning	A constructivist learning approach where learners are stimulated to conduct an investigation. It requires them to follow the scientific process of formulating questions; hypothesizing the result; investigating and analysing evidences; explaining the findings; and evaluating their arguments [51].	7	65, 53, 14, 57, 22, 13, 26
Kolb's experiential learning	Suggests that knowledge is gained through a four-stage cycle of experiential learning [54]: (1) concrete experience, (2) reflective observation, (3) abstract conceptualization and (4) active experimentation. Following this cycle, the learner encounters a concrete experience that encourages observation and reflection. This reflection of experiences creates abstract concepts which stimulates active experimentation resulting in new experiences. This cycle then repeats itself.	2	20, 61
Learning-by-doing	A form of learner-centered instructional approach that refers to improving skill development of the learner by practical experiences. Learning is, therefore, enforced by experiencing realistic tasks and interaction with the learning environment [12]	5	54, 75, 51, 4, 26
Problem-based learning	Learning approach that introduces challenging problems which the learners needs to solve. It encourages the learner to improve their critical thinking, problem-solving skills and metacognitive knowledge.	2	9, 59
Situated learning	Similar to learning-by-doing and depicts that transfer of learning is improved not only when the learner performs realistic tasks but also when the learner is situated in a realistic environment that is relevant to the learning activities [88]	2	62, 46
Constructivist-cognitive-contextual	Combination of constructivist, cognitive and contextual learning. Constructivist learning states that learners form their own constructs and adapt their knowledge based on interaction with the surrounding. Cognitivist learning refers to the thinking process when learning is taking place. Contextual learning allows learners to connect content with context by providing real life situations. [11]	1	11
Predict-observation-explain	A constructivist learning approach where "students make a prediction and interrogate the nature of situation they faced by combining their existing information with their experiences by using similar situations they faced in real world" [84]	2	63, 64
Not specified		53	

With N = number of studies.

Two studies have examined the scaffolding/guidance principle. Ullah et al. found that giving procedural guidance (i.e. step-by-step instructions) resulted in better procedural knowledge compared to no guidance by measuring time of completion and errors made [87]. However, it seemed that the participants score equally in declarative knowledge and skill-based outcome by test and hands-on lab practical evaluation. Borek et al. studied the effect of offering minimal guidance (inquiry), guidance when needed (tutored) or explicit instruction (direct instruction) [16]. They found that tutored approach resulted in better conditional knowledge than inquiry and direct instruction approaches. However, the results were not significantly different for declarative knowledge. They suggested that learners need sufficient guidance while using the virtual chemical laboratory, but not too much as they are demotivated by the lack of autonomous decision-making.

Table 8
Collection of instructional support elements used in virtual chemical laboratories of the reviewed publications.

Instructional support	Description	n	Ref.
Feedback	Information that is provided by an agent (e.g., teacher, book, self, game, etc.) as a consequence of the performance of the learner [39]. It has the purpose to direct learners to evaluate their progress towards a goal, identify knowledge gaps and reduce discrepancies between current understanding and the intended goal [48]	11	61, 19, 75, 24, 48, 47, 22, 13, 44, 50, 26
Scaffolding & guidance	An instructional technique that provides guidance and instructional support to the learner in an adaptive way [68]	8	18, 19, 65, 61, 22, 13, 44, 26
Pedagogical agent	The pedagogical agent, as Martha and Santoso [63] have stated, "… is an agent (single or multi) in the form of a virtual character equipped with artificial intelligence that can support the students' learning process and various instructional strategies in an interactive learning environment".	4	9, 51, 48, 24
modality	a multimedia principle states that it is more effective when information is given by a mixed modality presentation (partly visual and partly auditory) than only one modality type (either visual or auditory) [57]	6	5, 65, 48, 47, 75, 15
personalization	a multimedia learning principle explains that people learn more deeply when written or verbal presentations are in conversational style rather than formal style [64]	2	15, 48
Narrative element	Narrative depicts the use of a story as a teaching tool that allows the learner to construct a cognitive framework to structure the information and experiences [94]	2	9, 14
Reflection	Reflection is the metacognitive process of the learners where they reflect on their own learning process and the decisions they make during this process. [34]	1	47
Spatial contiguity	A multimedia principle which states that deep learning of the learner is better achieved when visual information (e.g., texts, pictures, animations) is presented near the relevant learning content rather than far away [64]	1	75
Not specified		55	

With N = number of studies.

Also, a study on pedagogical agents was performed by Makransky et al. [62]. They examined the effect of the virtual agent's appearance on the learning performance of boys versus girls between the ages of 13 and 16. A version of the commercial virtual laboratory Labster was altered to display a drone guide while another version used a human female guide. Results showed that boys performed better with the drone guide and girls performed better with the human female guide. The study concluded that gender matching of the pedagogical agent could

Table 9
Comparative studies with value-added research and the achieved results.

Instructional support	Comparison	Results	Ref.
Scaffolding & guidance	procedural vs no procedural guidance	procedural > no procedural guidance (pk) procedural = no procedural guidance (dk, sb)	65
	inquiry vs tutored vs direct instructions	tutored > inquiry = direct instruction (ck) tutored = inquiry = direct instructions (dk)	13
Pedagogical agent	robot drone vs human female	human female > robot drone (for girls) (dk, ck) robot drone > human female (for boys) (dk, ck)	48
Modality	voice vs text vs video instructions	voice > text = video instructions (dk, ck)	39
Spatial contiguity	co-located vs not co-located information	co-located > not co-located (dk)	75

With dk = declarative knowledge; pk = procedural knowledge; ck = conditional knowledge; sb = skill-based.

motivate the learner to do more effort to learn.

6. Discussion

6.1. Research on virtual chemical laboratories

In our review study we found that most publications performed media comparative studies in order to compare the performance between virtual labs and traditional teaching methods. Mainly quantitative evaluation methods were used for comparison, such as knowledge tests to examine the cognitive learning outcomes and lab practical assessments to assess practical laboratory skills. Similar to other reviews about virtual laboratories, declarative knowledge is the most studied learning outcome in this study [18,59]. Additionally, qualitative evaluation methods, such as questionnaires, interviews and observations, were also used in comparative studies to perform user studies.

Results of media comparison studies reveal that the effectiveness of virtual chemical laboratories varies widely depending on which traditional teaching method they are compared with. When comparing with passive media (e.g., classroom lectures, text or video), virtual labs are more effective for improving conditional knowledge but are, for some studies, not significantly different in terms of declarative knowledge. This means that for learning basic knowledge of chemistry facts and concepts, virtual labs are sometimes equal to passive media. This could be seen in the study of Makransky et al. [60] where this was explained by the cognitive overload (i.e. overwhelming cognitive capacity) of the learner while using VR systems. However, virtual labs do show better results when learners need to reason and apply chemical concepts to solve problems [42,47,60]. Virtual labs are able to provide dynamic visualisations in the sub-microscopic domain, while also offering an interactive platform for the learners [42]. This combination of visual support and high level of interactivity engages the learner to develop a deeper understanding of the learning content [24,86]. Combining virtual labs with passive media seems to result in a greater improvement as it reinforces the previously learned concepts (Davenport 2008).

Different results are found when virtual chemical laboratories are compared with traditional hands-on laboratories. These comparative studies suggest that virtual chemical laboratories are equally effective or sometimes better than hands-on laboratories regarding declarative knowledge, procedural knowledge and skill-based outcomes. These findings align with outcomes of other literature reviews in which also equal or improved results were observed between non-traditional (e.g., virtual, remote and at-home kit) and traditional laboratories [18,82]. While it is frequently argued that virtual labs cannot replace real hands-on laboratories [45,70,98], very little evidence has been found that virtual labs perform worse than hands-on labs [32]. This means that learners do learn procedural knowledge and laboratory skills in virtual environments where physical interaction is limited [72]. Especially when procedural guidance was provided during the virtual experiment, learners were able to perform better than their peers who were trained in the real laboratory [87]. However, it is possible that the lab practical experiments were so simple that simple interactions in virtual labs are sufficient to learn the techniques [90]. More research is required to investigate practical laboratory skills in virtual labs as there is a lack in studies that assess skill-based learning outcomes. So despite the media comparison of virtual and real labs steers towards equal effectiveness, virtual labs still have the advantage that no physical lab environment is needed, thus reducing cost, time, staff personnel and allowing easy accessibility [18]. Furthermore, a more effective use of virtual laboratories is to utilize them as a supplementary tool combined with hands-on laboratory resulting in improved cognitive and skill-based outcomes. When virtual labs are provided as pre-laboratory exercise, self-efficacy of students was significantly improved compared to hands-on lab only [55]. However, one must be careful not to overwhelm students with extra work load [93] or demotivate them with post-laboratory exercises [67].

Compelling results are found when attitude and usability towards chemistry laboratory are compared. Some studies show no difference in attitude [22,41,90,91], while other studies observed worse results when compared to hands-on laboratories [31,41]. Some students seem to believe traditional labs are more useful and easier to use than the virtual labs [31,41]. The reasons for these findings are still unclear, but authors suggests it could be due to self-selection bias [22] or instructor effect [40]. It can also be noticed that the studies of Enneking et al. [31] and Hensen et al. [41] have used the same virtual lab called LearnSmart Laboratories. So the discrepancies in attitude can be affected by the design of the virtual application. Nevertheless, comparison of affective measures between different media should be more rigorous to minimize any kind of bias.

Evaluative studies are the second most common research purpose in this review. These studies only considered the group using virtual chemical laboratories in order to evaluate the affective learning outcomes of the participants with questionnaires as the most used evaluation method followed by interviews and observations. The results of these user studies reveal, in general, positive attitude towards chemistry, good usability of the virtual lab and improved perceived self-efficacy; despite that some studies reported significant better results for hands-on laboratory. So in general, users consider the virtual laboratories to be satisfying, easy to use, helpful for learning and takes less time than real laboratory work. These positive reactions and opinions indicate that the students and teachers accept to use these systems as educational tool for laboratory practices. However, as stated previously, it depends on the design and implementation of each individual virtual laboratory. Usability issues should be resolved [73] and teachers should be well trained in using these applications [40] in order to provide better experiences.

Other evaluative studies demonstrated the possibility to evaluate procedural knowledge and skill-based outcomes by utilizing real-time assessment during the virtual experience [21,25,36,77,95]. This opens doors of opportunities for unintrusive transfer tests that could reduce test anxiety as the student is unaware of the assessment [80] and could avoid replication of real-life lab practical tests. However, we found a lack of studies using this evaluation methodology.

6.2. Technology use in virtual chemical laboratories

The technologies used for virtual chemical laboratories in our review study are distinguished in visual display output technology and kinaesthetic NUI input devices, where display technology are further divided in 2D and 3D graphics on monitor displays, and immersive VR headsets. This technology distinction is similar to the work of Ali and

Ullah [3], however in our case immersive VR and NUI are added because these innovative technologies are distinct from 2D and 3D Desktop in a way that they have the capability to simulate the chemical laboratory more realistically.

Virtual chemical laboratories with 2D Desktop technology have been used primarily to provide simple dynamic visualization and simulation of chemical experiments. They can display easy comprehendible animations that integrates the three levels of chemical representation [49]: macroscopic (e.g., color, solid, liquid), sub-microscopic (e.g., atoms and molecules) and symbolic level (e.g., chemical notation). With these animations, they support the learner's understanding of chemical reactions at sub-microscopic level, offering an advantage over traditional media [42]. Moreover, free experimentation is possible without requiring a real laboratory environment [96]. However, one of the drawbacks is that 2D representations are unable to provide realistic laboratory environments and actual lab skills [3,70]. Despite this lack of realism, they have been used consistently over the years with large population sizes. A reason for this could be that the simple geometries allow easy implementation via internet as they are less demanding in terms of computer performance and internet bandwidth than more advanced 3D VR systems [3].

A majority of publications have used 3D Desktop technology. These virtual chemical laboratories were developed with more realistic and more accurate representations of laboratory environments (e.g., fume hood, lab benches, cupboards with chemicals) and laboratory equipment (e.g., flasks, burettes, pipettes) than 2D Desktop laboratories. Additionally, users were also able to explore the simulated laboratory and freely manipulate 3D objects [22,73,90,97]. Authors agree that this level of realism and interactivity of virtual chemical laboratories can help students to familiarise with the laboratory prior to real laboratory practices [22,37,83]. Another use of realistic simulations is the possibility to simulate hazardous events that would otherwise be too dangerous to experience in real life. As such, unsafe laboratory handling can be recognised and good laboratory practices can be taught in the virtual environment without putting students at real risks [14,27,60]. However, virtual chemical laboratories in a 3D environment require more computing power due to the cost of rendering 3D objects with multiple polygons (i.e. geometries that a 3D object is made of) and interactions of the users simultaneously in real-time [26,83]. Nowadays, the huge improvement of recent computer technologies have made it easier to realize virtual environments with this high level of realism and interactivity, unlike in the early years of the computer age [23]. Still, 3D virtual chemical laboratories, that are displayed on a computer monitor using keyboard and mouse, are unable to bring the same feeling and practical handling as laboratories in reality [22,90].

Recently, immersive VR technology has been emerging as a promising educational tool for virtual chemical laboratories. With HMD VR devices, this technology offers a high level of immersion providing the feeling of really 'being there' in a virtual laboratory environment, whereas 3D Desktop is considered only as a low immersion technology because of the external screen [19]. The technological advancement of 3D stereoscopic depth, head position/rotation tracking and visual isolation from the real world makes the user believe that he or she is in an actual laboratory, thus taking a closer step to virtually replicating a chemical laboratory with high realism. Also, it is believed that the increased motivation and engagement positively influences the cognitive learning outcomes [69]. However, when comparing an immersive VR virtual lab with passive media and hands-on laboratory, studies reported equal effectiveness in declarative knowledge [30,60]. Other drawbacks are: more expensive than 2D and 3D Desktop; possibility to induce simulator sickness; and social isolation [35,71]. While immersive VR might not be the most efficient tool to teach declarative knowledge, perhaps it has a better use as behavioural and emotional training tool in certain laboratory situations [60]

In addition, visual display output technology can be combined with NUI input devices in order to enhance the physical authenticity of the virtual chemical laboratory. These NUI devices can register human gestures either by using sensors on wearable hardware (e.g., data gloves, haptic suits) or by visual detection of the human body (e.g., Leap Motion™, Kinect® devices). Using these advanced tracking technologies, it is possible to have realistic interactions (e.g., grabbing, pinching, pouring, etc.) with virtual objects in an ergonomic way [6,47]. Studies in this review have primarily used visual based NUI devices to perform chemical experiments [1,38,95]. The Kinect® NUI device has also been used to further increase the sense of presence and immersion by positioning the user's body within the virtual laboratory environment [25]. However, there are some limitations yet to be overcome when using visual based NUI technology such as, inability to precisely capture fine hand gestures, and to touch or smell the virtual objects [46,95]. To deal with some of these challenges, wearable NUI devices can be used to provide force feedback upon touching virtual objects, thus increasing the immersive feeling of being in a virtual laboratory. Nevertheless, combination of NUI technology with immersive VR devices promises great opportunities to exactly replicate real-life chemical laboratories and the practical skills in a virtual environment [95].

6.3. Instructional design of virtual chemical laboratories

In this systematic literature review, we have investigated which learning theory and instructional support elements have been implemented in virtual chemical laboratories. There is a common argument in literature that learning theories are often neglected in studies of educational technology [43]. Especially with the use of VR technologies, integration of instructional design features are seen as a necessity [60]. Unfortunately, the findings in our literature study could not disprove this argument, as a majority of the reviewed publications did not specify a learning theory. Learning theories are important because they can describe, explain and predict how people learn when using certain technologies [43]. In this way, instructional design of virtual chemical laboratories can be adapted to these theories to maximize learning mechanisms. The studies in this review that did specify learning theories, have most frequently mentioned inquiry-based learning, discovery learning, learning-by-doing and experiential learning. This is not surprising because inquiry and discovery learning are inherent characteristics of laboratory instructions [28]. The interactivity and autonomous learning are aspects of virtual chemical laboratories that make these learning environments constructivist and learner-centered. This allows the learner to create a more meaningful understanding of chemical concepts [84]

Another aspect of instructional design is the instructional support that the learner receives during the virtual learning experience. As seen in the study of Makransky et al., effective learning in virtual environments can be hindered by cognitive overload of the learner [60]. Therefore, providing instructional support could manage this cognitive load more efficiently and could assist the learner when needed [94]. Instructional support elements, such as feedback, scaffolding/guidance and modality, have been used the most in the studies of this review. Although most of these studies have only briefly mentioned these features, more can be learned from studies that have performed value-added research on instructional support principles. According to these studies, it is suggested that virtual chemical laboratories are most effective when instruction is given near the location of the learning content (i.e. spatial-contiguity principle) using audio source (i.e. modality principle) and when guidance (e.g., procedural instruction, hints, feedback) is given only when needed [16,47,87,97]. However, not enough studies have conducted value-added research in the context of virtual chemical laboratories. Also, similar to learning theories, a majority of the studies have not specified any instructional support element. Eventually, we have come to a point where it seems that we should focus more on how virtual chemical laboratories are designed rather than merely comparing different instructional media [44]. In this way, we can find a more meaningful progress in research leading to more effective virtual laboratory systems.

7. Conclusion

This literature review shows an analysis of published research that has been done on virtual laboratories for chemistry education. The current review adds on previous reviews in this field because we focused not only on the effectiveness of virtual labs in chemistry education but also included an in-depth analysis on both novel technology and instructional design.

The results of this review conclude that virtual chemical laboratories are viable as an effective complementary tool or as an alternative to hands-on laboratories, despite several publications have argued that they cannot be used as replacement [45,70,82,98]. Virtual labs can provide better results in learning outcomes of all domains (i.e. cognitive, affective and skill-based) than traditional passive media and they are considered to be equally as effective and sometimes better than real hands-on laboratories. A more effective use is to combine virtual labs with passive media or with hands-on labs. However, important considerations need to be taken in terms of choice of technology and instructional design.

Technologies used in virtual chemical laboratories range from simple 2D graphics to more sophisticated 3D representations of the real laboratory. Even though 3D Desktop has been used more than 2D Desktop and immersive VR, each of these technologies have their own benefits and have different purposes. One might opt for a low-cost easy to implement 2D virtual labs to teach chemical reactions, or a more costly complex 3D virtual lab to replicate experiments with simple interactions. If high realism is required, the more expensive immersive VR technology and NUI input devices can be used.

This review also found that most studies have not considered learning theories or instructional support in the instructional design. However, these elements are essential to efficiently manage the learner's cognitive load and provide sufficient assistance when learners are struggling.

This literature review can be helpful for researchers, teachers and instructional developers to implement effective technologies and instructional design elements that are based on research on virtual chemical laboratories. Even though virtual laboratories cannot provide the real experience and skills as real laboratories with current technology, they are still effective tools for distance learning. Especially for situations when distance learning is the only option, such as in pandemic outbreaks, schools that cannot afford the cost of real laboratories or individuals who are unable to attend certain laboratory sessions.

7.1. Future research

This review identifies a lack of studies that investigate the learning of practical skills in the virtual laboratory experiences. The impact of realistic laboratory handling in virtual chemical laboratories using immersive VR and NUI technology on all learning domains must be investigated more profoundly. Practical skills can be assessed in real-time during the virtual experience, but this approach needs further investigation on its reliability and validity. Finally, future research should focus more on value-added research rather than media comparative studies in order to advance in effective instructional design research of virtual chemical laboratories.

7.2. Limitations

Several limitations of this literature review are identified in this section. Firstly, there is a possibility that we have overlooked an unknown number of publications that could be included in this review due to: only one database was used (i.e. Web of Science); and some publications were excluded as they did not clearly specify a chemical laboratory practice or technology. Nevertheless, this limitation should not have affected our conclusions severely. Secondly, the data of comparative and evaluative studies were not compared quantitively in detail. In order to know the effect size of how much the effectiveness is of virtual chemical laboratories, a systematic meta-analysis is needed. Finally, other immersive technologies, such as CAVE and augmented reality were not included because they are not fully virtual and still require a physical space in the real world.

Declaration of Competing Interest

None.

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Appendix

Appendix A. List of categories and their description used for coding the reviewed publications

Variables	Category	Description
Basic publication information		Author, title, publication year
Research purpose	Comparative study	Studies that investigated two or more intervention groups either comparing the media (media comparison) or the design of the virtual laboratory (value-added research) [64]
	Evaluative study	Studies that only considered the virtual lab intervention group to evaluate performance assessment, user study or correlation study
	Technical study	Studies that have not performed measurements but describes the design and development of the virtual chemical laboratory
Sample size		Number of participants that were involved in the study
Sample population	Elementary school	Children until 11 years old in elementary school
	Middle/High school	Students between 11 and 18 years old in middle or high school
	University	Students between 18 and 24 years old in university
	Teachers	Adults older than 24 years old working as teachers
Comparison	Virtual lab vs passive media vs hands-on lab (or a combination)	The comparison between a virtual chemical laboratory with passive media (e.g., classroom lectures, video, text manual, demonstrations) or with traditional hands-on laboratory, including a combination of these media (e.g., virtual lab + hands-on lab or virtual lab + passive media).

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(*continued*)

Variables	Category	Description
Evaluation method	Test	A quiz testing cognitive outcomes of the student right before (pre-test) or/and after (post-test) the intervention.
	Experiment	A chemical experiment performed in a traditional hands-on laboratory as evaluation of the student's laboratory skills
	Real-time assessment	Embedded performance evaluation within the digital application and recorded in data log files.
	School grade	The school grade of the student after an academic period (usually a trimester or semester)
	Questionnaire	A survey with questions to be answered by the participant
	Interview	A structured conversation with the participant containing questions to be answered
	Observation	Findings by direct observation of the participant during the intervention
Learning outcome	Cognitive	Learning outcomes of the cognitive dimension (including declarative, procedural and conditional knowledge)
	Affective	Learning outcomes of the affective dimension (including self-efficacy, attitude, usability)
	Skill-based	Learning outcomes of the skill-based dimension (including laboratory handling skills)
Technology type	2D Desktop	Two dimensional representation of the lab environment or equipment using a desktop monitor display
	3D Desktop	Three dimensional representation of the lab environment or equipment using a desktop monitor display
	Immersive VR	Immersive virtual reality device that allows a high level of immersion (including head-mounted displays)
	NUI (2D, 3D or imVR)	Natural user interfaces that uses ergonomic movements or gestures as input to control the virtual lab (including spatial tracking, hand gestures, body gestures)
Instructional design	Instructional approach	Learning theories applied in the virtual lab
	Instructional support	Instructional support elements that serve as an aid for the user's cognitive processing in the virtual lab

Appendix B. Coding scheme of the 76 reviewed publications

Nr.	**Author**	**Tech**	**Method**	**Size**	**Population**	**Learning outcome**	**Evaluation method**	**Comparison**	**Media comparison**	**Learning theory**	**Instructional support**
1	**(Achuthan, 2015)**	2D	C (media)	141	University	Cog (dk)	test	virtual vs virtual + hands-on vs hands-on	virtual = virtual + hands-on > hands-on (dk)	Not specified	Not specified
2	**(Agbonifo, 2020)**	3D	E (user study)	50	Middle/ High, University	Aff (us)	quest	n/a		Not specified	Not specified
3	**(Aldosari, 2015)**	NUI (3D)	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
4	**(Aldosari, 2016)**	NUI (3D)	E (user study)	90	University	Aff (us)	quest	n/a		Learning-by-doing	Not specified
5	**(Ali, 2014)**	NUI (3D)	C (media)	14	Middle/High	Cog (dk), Aff (us, se), Skill	test, lab pr, quest	virtual vs passive	Virtual > passive (dk, sb)	Not specified	modality
6	**(Al-khalifa, 2016)**	NUI (2D)	E (user study)	16	Elementary	Aff (us)	quest, obs	n/a		Not specified	Not specified
7	**(Almazaydeh, 2016)**	2D	E (user study)	25	Middle/High	Aff (us)	quest	n/a		Not specified	Not specified
8	(Alqadri 2018)	2D	E (performance)	30	Middle/High	Cog (dk, pk)	test	n/a		Direct instruction	Not specified
9	**(Annetta, 2014)**	3D	E (performance)	31	Teachers	Cog (dk), Other	test, quest, interv	n/a		Problem-based learning	Pedagogical agent, feedback, narrative
10	**(Astuti, 2019)**	imVR	C (media)	96	Middle/High	Aff (att)	quest, obs	virtual vs virtual + hands-on vs hands-on	virtual + passive = virtual + hands-on > hands-on (att)	Not specified	Not specified
11	**(Bakar, 2013)**	3D	C (media)	61	Middle/High	Cog (ck)	test, interv, obs	virtual vs passive	Virtual > passive (ck)	Cognitivism-constructivism-contextual approach	Not specified
12	**(Bell, 2004)**	3D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
13	**(Borek, 2009)**	2D	C (value-added)	87	University	Cog (dk, ck), Aff (us)	test, quest	Inquiry vs tutored vs direct instruction	Tutored condition = inquiry = direct instruction (dk) Tutored condition > inquiry or direct-instruction (ck)	Inquiry learning	feedback, scaffolding & guidance
14	**(Chee, 2012)**	3D	C (media)	39	Middle/High	Cog (dk pk), Aff (att)	test, quest, interv, obs	virtual vs passive	virtual > passive (dk, pk)	Inquiry-based, learning-by-doing, embodied learning	narrative
15	**(Clemons, 2019)**	2D	E (user study)	428	University	Aff (us)	quest, interv	n/a		Not specified	Modality, personalization
16	**(Cuadros, 2015)**	2D	E (performance)	60	Middle/High	Cog (pk)	r-t assess	n/a		Not specified	n/a
17	**(Dalgarno, 2009)**	3D	C (media)	133	University	Cog (dk), Aff (att, us, se)	test, quest, interv	virtual vs hands-on	virtual = hands-on (dk, att, se)	Not specified	
18	**(Davenport, 2018)**	2D	C (media)	1334	Middle/High	Cog (dk, pk)	test, interv, r-t assess	virtual vs virtual + passive	virtual + passive > virtual (dk)	Not specified	Scaffolding & guidance
19	**(Desai, 2017)**	NUI (3D)	E (performance, user study)	31	Middle/High	Aff (us), Skill	quesst, r-t assess	n/a		Not specified	Scaffolding feedback

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Nr.	Author	Tech	Method	Size	Population	Learning outcome	Evaluation method	Comparison	Media comparison	Learning theory	Instructional support
20	**(Dholakiya, 2019a)**	3D	E (user study)	45	University	Aff (us)	quest	n/a		Kolb's experiential learning	Not specified
21	**(Dholakiya, 2019b)**	3D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
22	**(Donnelly, 2013)**	2D	E (user study)	4	Teachers	Aff (att)	quest, interv, obs	n/a		Inquiry-based learning	Scaffolding &guidance, feedback
23	**(Duan, 2020)**	imVR	E (user study)	45	University	Aff (us)	quest, interv	n/a		Not specified	n/a
24	**(Dunnagan, 2020)**	imVR	C (media)	75	University	Cog (dk)	test	virtual vs hands-on	virtual = hands-on (dk)	Not specified	Pedagogical agent
25	**(Enneking, 2019)**	3D	C (media)	1141	University	Cog (dk, pk, ck), Aff (att), Skill	test, quest, lab pr	virtual + hands-on vs hand-on	virtual + hands-on = hands-on (dk,pk,ck,sb) virtual + hands-on < hands-on (att)	Not specified	Not specified
26	**(Gal, 2015)**	2D	E (performance)	306	University	Cog (pk, ck)	r-t assess	n/a		Learning-by-doing, inquiry learning	feedback, scaffolding
27	**(Georgiou, 2007)**	3D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
28	**(Gervasi, 2004)**	3D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
29	**(Han, 2017)**	NUI (imVR)	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
30	**(Hawkins, 2013)**	2D	C (media)	169	University	Cog (dk), Skill	test, lab pr	virtual vs hands-on	virtual = hands-on (dk, sb)	Not specified	Not specified
31	**(Hensen, 2019)**	3D	C (media)	396	University	Aff (att, us)	quest	virtual vs hands-on	virtual < hands-on (att)	Not specified	Not specified
32	**(Hensen, 2020)**	3D	C (media)	717	University	Cog (dk, ck), Aff (att), Skill	test, quest	virtual vs hands-on	virtual = hands-on (dk, ck, att)	Not specified	Not specified
33	**(Herga, 2012)**	2D	C (media)	38	Elementary	Cog (dk, ck)	test	virtual vs passive	virtual > passive (dk, sk)	Not specified	Not specified
34	**(Herga, 2015)**	2D	C (media)	225	Elementary	Cog (dk, ck)	test	virtual vs passive	Virtual = passive (dk) Virtual > passive (ck)	Not specified	Not specified
35	**(Herga, 2016)**	2D	C (media)	109	Elementary	Cog (dk, ck)	test	virtual vs passive	Virtual *b* > passive (dk, ck)	Not specified	Not specified
36	**(Ikhsan, 2020)**	imVR	C (media)	96	Middle/High	Cog (dk)	test	virtual vs virtual + hands-on vs hands-on	virtual + passive = virtual + hands-on > hands-on (ck)	Not specified	Not specified
37	**(Ikram, 2015)**	NUI (3D)	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
38	**(Irby, 2018)**	2D	C (media)	67	University	Cog (dk, ck)	test, obs	Virtual + hands-on vs hand-on	virtual + hands-on = hands-on (dk,ck)	Not specified	Not specified
39	**(Jagodzinski, 2015)**	NUI (2D)	C (media, value-added)	200	Middle/High	Cog (dk, ck), Aff (us, se)	test, quest	Media: virtual + passive vs passive Value-added: voice vs text vs video instructions	Media: virtual + passive > passive (dk, ck) Value added: voice > text = video (dk,ck)	Not specified	Not specified
40	**(Jagodziński, 2014)**	NUI (2D)	C (media)	150	Middle/High	Cog (dk, ck), Aff (us, se)	test, quest, obs	virtual vs passive	Virtual > passive (sk) virtual = passive (dk)	Embodied cognition	Not specified
41	**(Jorda, 2013)**	3D	E (user study)	15	University	Aff (us)	quest	n/a		Not specified	Not specified
42	**(Kim, 2016)**	NUI (3D)	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
43	**(Kim, 2017)**	NUI (3D)	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
44	**(Kim, 2019)**	imVR	T	n/a	n/a	n/a	n/a	n/a		Not specified	Scaffolding & guidance, feedback
45	**(Kolil, 2020)**	2D	C (media)	1225	University	Aff (se)	quest	virtual + hands-on vs hands-on	virtual + hands-on > hands-on (se)	Not specified	Not specified
46	**(Lau, 2017)**	3D	T	n/a	n/a	n/a	n/a	n/a		Situated learning	Not specified
47	**(Makransky, 2019a)**	imVR	C (media)	105	University	Cog (dk, ck), Aff (se), Skill	test, lab pr, quest, interv	virtual vs passive	virtual = passive (dk) virtual > passive (ck)	Control value theory, embodied cognition	Pedagogical agent, modality, feedback
48	**(Makransky, 2019b)**	imVR	C (value-added)	66	Middle/High	Cog (dk, ck), Aff (social)	test, quest	Human female vs robot drone	Human female > robot drone (for girls) (dk, ck) Robot drone > human female (for boys) (dk, ck)	Not specified	Pedagogical agent, modality, feedback
49	**(Martínez-Jiménez, 2003)**	2D	C (media)	274	University	Cog(dk, pk, ck), Skill	test, lab pr	virtual + hands-on vs hands-on	Virtual + hands-on > hands-on (dk,pk,ck,sb)	Not specified	Not specified
50	**(Moozeh, 2020)**	2D	E (user study)	46	University	Aff (us)	quest	n/a		Not specified	feedback
51	**(Morozov, 2004)**	3D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Pedagogical agent
52	**(Penn, 2019)**	2D	E (user study)	50	University	Aff (att, us, se)	quest, interv	n/a		Not specified	Not specified

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Nr.	Author	Tech	Method	Size	Population	Learning outcome	Evaluation method	Comparison	Media comparison	Learning theory	Instructional support
53	**(Pyatt, 2012)**	2D	C (media)	184	Middle/High	Cog (dk, pk), Aff (us, att), Skill	lab pr, quest	virtual vs hands-on	trial 1: virtual = hands-on (dk,pk) trial 2: virtual > hands-on (dk,pk)	Inquiry-based, guided-discovery, learning-by-doing	Not specified
54	**(Qvist, 2015)**	3D	E (user study)	29	University	Aff (us)	quest, interv, obs			learning-by-doing	Not specified
55	**(Ramos, 2016)**	2D	E (user study)	120	University	Aff (us)	quest	n/a			Not specified
56	**(Ratamun, 2018)**	2D	C (media)	147	Middle/High	Cog (dk, ck)	test	virtual vs hands-on	virtual < hands-on (dk,ck)	inquiry-based learning	Not specified
57	**(Rowe, 2018)**	2D	C (media)	160	University	Cog (dk), Aff (us), Skill	quest, grade	1: virtual vs hands-on 2: virtual + passive vs passive	1: virtual = hands-on (dk, sb) 2: virtual + passive > passive (dk)	inquiry-based learning	Not specified
58	**(Sampaio, 2014)**	3D	E (performance, user study)	6	Middle/High	Cog (pk), Aff (us)	quest, obs, interv, r-t assess	n/a		Not specified	Not specified
59	**(Scherer, 2012)**	2D	E (other)	162	Middle/High	Cog (ck)	quesst, r-t assess	n/a		Problem-solving based design	Not specified
60	**(Solikhin, 2019)**	2D	C (media)	87	Middle/High	Cog(dk), Aff (us)	test, quest	virtual vs virtual + hands-on vs hands-on	virtual + hands-on > virtual > hands-on (dk)	Not specified	Not specified
61	**(Su, 2019)**	3D	C (media)	72	Middle/High	Cog (dk), Aff (se)	test, quest	virtual vs passive	virtual > passive (dk)	Kolb’s experiential learning, cognitive load theory	Feedback, scaffolding & guidance
62	**(Tarng, 2017)**	3D	C (media)	80	University	Cog (dk), Aff (us)	test, quest	virtual vs hands-on	Virtual > hands-on (dk)	Situated learning	Not specified
63	**(Tatli, 2012)**	3D	C (media)	90	Middle/High	Other	quest, interv, obs	virtual vs passive + hands-on vs passive	virtual > passive + hands-on > passive	predict-observe-explain (POE)	Not specified
64	**(Tatli, 2013)**	3D	C (media)	90	Middle/High	Cog (dk)	test, obs, interv	virtual vs hands-on	Trial 1: virtual = hands-on (dk) Trial 2: virtual > hands-on (dk)	Constructivist approaches	Not specified
65	**(Ullah, 2016)**	NUI (3D)	C (media, value-added)	57	Middle/High	Cog (dk, pk), Aff (us, se), Skill	test, quest, r-t assess, lab pr	Media: virtual vs hands-on Value-added: procedural vs non-procedural	Media: virtual > hands-on (dk, sb) Value-added: procedural > non-procedural (sb)	Inquiry-based, discovery based learning	Modality, scaffolding & guidance
66	**(Wang, 2018)**	imVR	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
67	**(Winkelmann, 2014)**	3D	C (media)	12	Middle/High	Cog (dk, ck), Aff (att, us)	test, quest	virtual vs hands-on	virtual = hands-on (dk,ck, att)	Not specified	Not specified
68	**(Winkelmann, 2017)**	3D	C (media)	122	University	Cog (dk), Aff (us), Skill	test, quest, interv, obs, lab pr	virtual vs hands-on	virtual = hands-on (dk, sb)	Not specified	Not specified
69	**(Winkelmann, 2020)**	3D	C (media)	279	University	Cog (dk), Aff (att, us), Skill	test, quest, lab pr	virtual + hands-on vs hands-on	virtual + hands-on = hands-on (dk, att, sb)	Not specified	Not specified
70	**(Wolski, 2019)**	NUI (2D)	C (media)	150	Middle/High	Cog (dk, ck)	test	virtual vs passive	virtual = passive (dk) virtual > passive (ck)	Not specified	Not specified
71	**(Woodfield, 2004)**	3D	E (user study)	616	University	Aff (us, se)	quest, interv, obs	n/a		Not specified	Not specified
72	**(Woodfield, 2005)**	3D	E (performance)	963	University	Cog (dk, ck), Aff (us)	quest, interv, obs, grade	n/a		Not specified	Not specified
73	**(Wu, 2019)**	NUI (imVR)	E (performance, user study)	28	University	Aff (us), Skill	quest, r-t assess	n/a		Not specified	Not specified
74	**(Yaron, 2010)**	2D	T	n/a	n/a	n/a	n/a	n/a		Not specified	Not specified
75	**(Zayas-Perez, 2009)**	3D	C (value-added)	48	University	Cog (dk)	test	Co-located vs not co-located	Co-located > not co-located (dk)	Learning-by-doing	spatial contiguity, feedback, modality
76	**(Zhong, 2014)**	3D	E (user study)	14	Teachers	Aff (us)	quest, interv	n/a		Not specified	Not specified

Abbreviations: 2D = 2D Desktop; 3D = 3D Desktop; imVR = immersive VR; NUI = Natural User Interface; C = comparative; *E* = evaluative; *T* = technical, Cog = cognitive domain, Aff = affective domain, Skill = skill-based domain, dk = declarative knowledge; pk = procedural knowledge; ck = conditional knowledge; att = attitude; se = self-efficacy; us = usability; quest = questionnaire; interv = interview; r-t assess = real-time assessment; obs = observation; lab pr = lab practical; n/*a* = not available.

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