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Simulations in Science Education. A Systematic Literature Review

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Abstract

Despite numerous initiatives in recent decades, there is still a shortage of approximately 449,300 STEM professionals in Germany. Furthermore, the increasing digitalization of all areas of life is increasing not only the demand for IT professionals but also the requirements of companies and employees with digital expertise. In line with this development, there are calls to strengthen the use of digital media in schools. In particular, simulations offer great potential for science lessons due to their high degree of interactivity and similar characteristics to experiments. A comprehensive literature review was conducted to identify research gaps. A multistage process, which included a title analysis, abstract analysis, and full-text analysis, was employed to analyze 42 full texts. These were qualitatively evaluated and discussed. The majority of studies looked at simulations in isolation or compared simulation-based teaching with other forms of learning. It was found that simulations promote self-efficacy and knowledge growth, among other things. However, no clear conclusions could be drawn with regard to interest and cognitive load.

Keywords: digitalization; education; international; review; Science; simulation; STEM

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1. Simulations as a "new" medium in schools and science lessons?

In view of the low attractiveness of science degree programs (Statistisches Bundesamt, 2023) and the high drop-out rate of almost 50 percent in these subjects (Heublein et al., 2022), there is a need to promote interest in science among young people. As early as Hoffmann and Lehrke (1986) found in their work that the initial interest in scientific phenomena is not only lost in upper secondary school but also with the transition to secondary school. It would, therefore, appear that interest must be maintained during this time in particular. Science lessons are predestined to be the main meeting place for this, as schools are the main providers of resources and teaching expertise in the German school system. Science lessons have had to change significantly, especially since 2020, as many working methods, such as experimentation, were no longer feasible due to the coronavirus. The response to the new teaching and learning circumstances was a greatly "accelerated" digitalization of teaching, whereby the digital media used served more to communicate and transfer working materials (worksheets, tasks) than to fundamentally innovate didactics (Henne et al., 2021).

Like almost no other subject, the natural sciences allow learners to independently generate interesting insights, including for third parties, by means of the scientific path of knowledge and to (co)design, experience, and reflect on the entire process (Huber et al., 2009; Mieg, 2020). Simulations can help here, as they are able to convey specialized knowledge as well as concrete scientific practices and working methods (Cayvaz et al., 2020). Motivating and interesting science lessons can be an important tool for providing the labor market with well-trained and motivated students in the STEM field in the future (Lee et al., 2018; Wegner & Tölke, 2016), who are better prepared for the tasks in the scientific world thanks to the knowledge they have already acquired about scientific topics and working methods. This can help reduce the drop-out rate in STEM subjects (Fischer et al., 2021), as learners are both better informed about the subjects and trained in some scientific practices.

In this way, the initial curiosity can be intuitively channeled into more formal paths. Experimentation is an essential part of the path to knowledge (Stiller et al., 2020). In view of the advancing digitalization in private and school contexts (Mußmann et al., 2021), new opportunities are also emerging for science lessons. For example, digital media can be actively incorporated into lessons and help to improve and transform the learning process (SAMR model, Puentedura 2020). The use of simulations in the classroom offers the opportunity to prevent loss of interest as well as to fully utilize the potential of digital media and enable a deeper understanding of the subject matter through a redefinition (SAMR model) of teaching and learning processes. Jebeile (2017) shows in her comparative analysis that the experiment and simulation have many common characteristics as core elements of the scientific path to knowledge. For example, both allow exploration, are highly interactive and can visualise phenomena. In addition, experiments and (some) simulations develop over time. What is meant here is that state variables change over time in both the experiment and the simulation. In contrast to the animation, which also develops over time, additional parameters can be actively changed in the simulation (Betrancourt, 2005), whereupon the simulation changes dynamically, similar to the manipulation of experimental settings. Jebeile (2017) also attributes the so-called black box effect, i.e., the fact that the underlying processes whose effects lead to the observed result are not known, to both the experiment and the simulation. The explorative character of learning can, therefore, be promoted not only by experiments but also by simulations. Through interactive simulation, which is initially new for (unknowing) observers, phenomena can be investigated so that research-based learning (Mieg, 2020) can take place. It is important to remember that simulations are artificial (simplified) replicas based on mathematical models (Zauner and Schrempf, 2009). Due to their modeling character, they are, therefore, usually free of errors. A study by Bumbacher et al. (2018) investigated whether artificial noise influences students' understanding of concepts. Although no differences in understanding were found, there were differences in experimentation strategies.

Noise led to more productive strategies and increased students' cognitive engagement, as they had to decide in their measurements whether the values were caused by their manipulation or by statistical noise (Bumbacher et al., 2018). This critical reflection, which is typical for real experiments, is simply not present in simulations. It may, therefore, be advisable to use simulations and real-life experiments together in order to benefit from both forms (Blikstein et al., 2016). When using multimedia learning material, various variables have been identified as significant influencing factors on the effectiveness of the learning medium in question, including the type of use, the duration of the intervention, the learning content, and the target group (Zwingenberger, 2009). Simulations have been used and researched in science and education for many years. However, previous reviews have mostly focused on the two categories of achievement outcomes and non-cognitive outcomes (D'Angelo et al., 2014) or on specific effects of simulations on skills such as conceptual understanding (Widiyatmoko, 2018). For this reason, an open-ended analysis of the findings was carried out in order to identify further aspects that have not yet been investigated and to identify research desiderata.

In line with the design-based research approach (DBR, Shavelson et al., 2003), this review is intended to represent the preliminary examination for a research project on the topic of simulations in science education. Design-based research is characterized by its recursive, practice-oriented research approach, in which one or more prototypes are developed after a preliminary test and then undergo an assessment. Based on the results of the assessment, the prototypes are further developed and then go through the assessment phase again (Kramer & Wegner, 2022; Schäfers & Wegner, 2021; Schmiedebach & Wegner, 2021). As a preliminary examination, a systematic literature review on the topic of simulations in science teaching is presented below. The theory to date provides evidence (Blikstein et al., 2016; Cayvaz et al., 2020; Jebeile, 2017; Puentedura, 2020) that simulations can add value to science teaching. In order to empirically substantiate this thesis, a comprehensive literature review was carried out to provide information on the use and impact of simulations in science lessons. Guiding and research questions were formulated in the review to be able to categorise the findings of the literature review later on and derive any implications for the project [name of project]. The following research questions were selected:

- What influence does the use of simulations have on students, and how have simulations been used in science lessons so far?
- What are the advantages and disadvantages of implementing simulations in science lessons compared to traditional teaching and real experiments?
- In view of the relevance of other factors influencing the effectiveness of multimedia learning materials, the question arises as to which framework conditions promote the implementation of and learning with simulations in science lessons.
- How do students perceive the simulation in the classroom in terms of affective factors?

2. Materials and methods

In line with the design-based research approach (Shavelson et al., 2003), the existing state of research was first reviewed, the most important results of research on the topic of "simulations in science education" were summarized, and these were subsequently discussed. This provides an indication of how simulations can be profitably integrated into science education and what effects could be demonstrated with different formats of integration. Following the presentation and discussion of the results, implications, and existing research desiderata for the project [name of project] were identified. On this basis, research desiderata were identified. From these, research questions and hypotheses based on educational theory were derived, which in turn are to be investigated in the project [project name]. In order to cover the current state of research as completely as possible, a systematic literature review was carried out, which is described below.

2.1. Search strategy

To enable a comprehensive analysis of existing findings, both the international database "Web of Science" (Figure 1) and the database "FIS Bildung - Fachportal Pädagogik" (Figure 2) were used (cut-off date May 25, 2022). The advantages of these databases are their large scope and the cross-disciplinary search. While the Web of Science database already offers a refined search using the terms "simulation*", "bildung*", "Naturwissen*", "MINT*", "physik*", "Chemi*", "Informatik*" and their English equivalents in the categories Topic, Abstract and Title, the search in FIS Bildung - Fachportal Pädagogik has been restricted to the so-called free text search of the terms "Simulation*", "Bildung*" and "Naturwissenschaft*" or "MINT*", also due to the different search interface, to ensure the most comprehensive search possible. In particular, publications from the medical sector were excluded from the "Web of Science" search, as it turned out that simulations are already extensively used and researched in professional medicine for the training of prospective doctors and nursing staff. However, since adult education was excluded due to the limited target group of students, this sector was preemptively excluded by excluding the term "medical".

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(TP=("simulation*") OR TI=("simulation*"))
AND (((TP=("education*") OR TI=("education*") OR AB=("education*") OR
TP=("education*") OR TI=("education*") OR AB=("education*")))
AND (TP=("science*") OR TI=("science*") OR AB=("science*") OR
TP=("Naturwissen*") OR TI=("Naturwissen*") OR AB=("Naturwissen*")OR
TP=("Stem*") OR TI=("Stem*") OR AB=("Stem*") OR TP=("MINT*") OR
TI=("MINT*") OR AB=("MINT*") OR TP=("PHYSIC*") OR TI=("PHYSIC*")
OR AB=("PHYSIC*") OR TP=("PHYSICS*") OR TI=("PHYSICS*") OR
AB=("PHYSICS*") OR TP=("CHEMI*") OR TI=("CHEMI*") OR
AB=("CHEMI*") OR TP=("COMPUTER SCIENCE*") OR TI=("COMPUTER
SCIENCE*") OR AB=("COMPUTER SCIENCE*") OR
TP=("INFORMATIK*") OR TI=("INFORMATIK*") OR
AB=("INFORMATIK*") OR TP=("TECHNIK*") OR TI=("TECHNIK*") OR
AB=("TECHNIK*") OR TP=("TECHNOLOGICAL EDUCATION*") OR
TI=("TECHNOLOGICAL EDUCATION*") OR AB=("TECHNOLOGICAL
EDUCATION*")) NOT (TS=(Medical*) OR TI=(Medical*)))
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Figure 1. Search terms in the database "Web of Science".

In view of the rapid increase in digitality since the year 2000 (Elstner et al., 2022), only literature from the years 2000 to 2022 was included in both databases. In order to be considered, the studies analyzed had to have their learning content/contexts anchored in the STEM subjects (mathematics, computer science, natural sciences, and technology). In addition, due to the author's language restrictions, only German or English-language publications were considered in the literature review. The English equivalent of the acronym MINT is "STEM", but this is not a direct translation.

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( ( ( ( (free text: SIMULATION*) and (free text: EDUCATION*) ) and (free text:
SCIENCE*) ) and (year >=2000) ) or (free text: STEM*)
```

Figure. 2. Search terms in the database "FIS Bildung - Fachportal Pädagogik"

While STEM covers the subject areas mentioned above, STEM is used to abbreviate the subjects of science (natural sciences), technology (in the sense of computer science, but also industrial design), engineering, and mathematics. A direct comparison shows that subjects such as technology, which is listed separately in German-speaking countries, are categorized under the two subjects of technology and engineering in English-speaking countries. Although the categorization is slightly different, the acronyms cover the same subjects overall and can, therefore, be used synonymously for research purposes. The literature was managed using Citavi 6.14.4.0 software.

2.2. Exclusion and selection criteria for sources

In order to ensure a focus on the research interest, some limitations were set for the search criteria. For example, this literature review only included studies whose target group (test subjects) were pupils from primary school to the highest level of general education, which corresponds to an age range of five to 20 years. Studies in which only students or teachers were explicitly analyzed were excluded to avoid any false implications in this regard. In addition, the following further limitations were defined. After removing duplicates, both databases returned 1309 publications, of which 964 were excluded due to their title. After the abstract analysis of the remaining publications, a further 234 studies were eliminated due to a lack of fit. Of the remaining 111 publications, a further 69 publications could be sorted out after the full-text analysis, so 42 publications were included in this literature review (Figure 3).

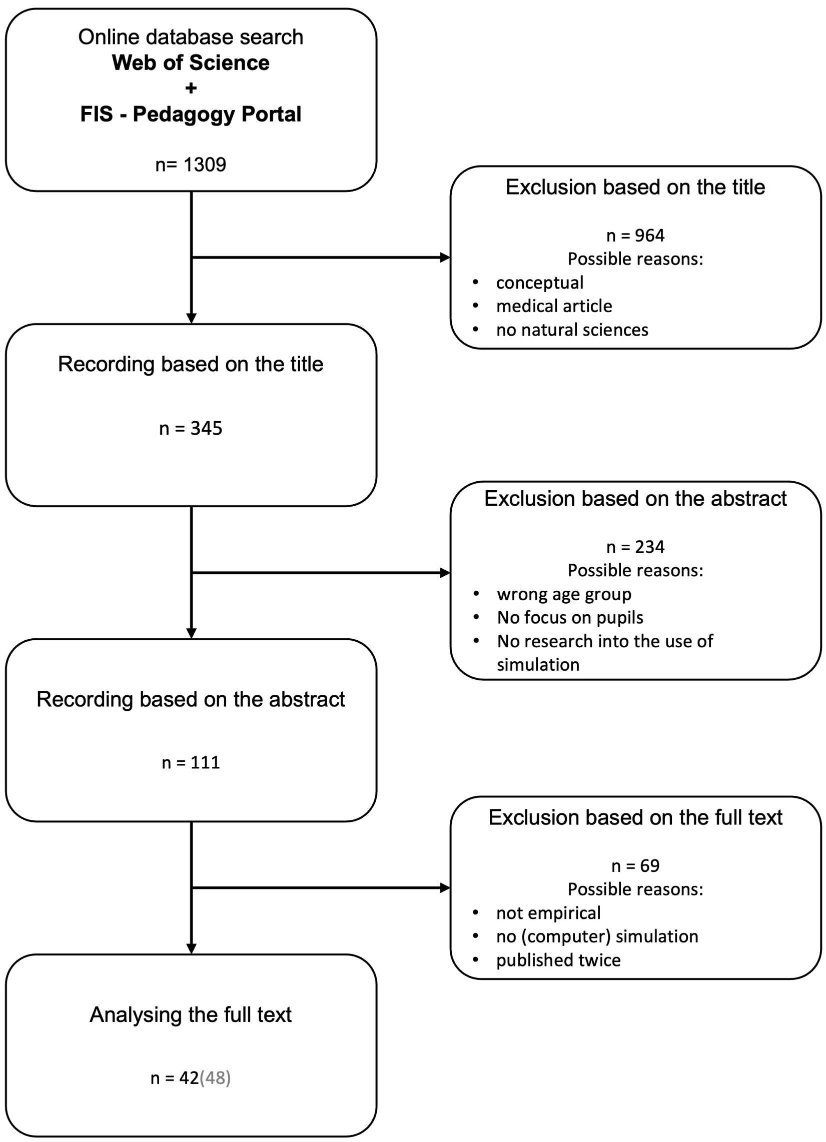

Figure 3. Flowchart of the database search

The studies included in the literature review met the following criteria. There is a match in the search terms in at least one of the two databases. A match of search terms for a title increases the probability of obtaining relevant information for the literature review through the study. This also ensured a systematic selection of sources.

The empirical study focused on the use of simulations in science lessons. In order to enable an evidence-based discussion of the research interest, it is necessary to draw on empirical findings. For this reason, only those titles that were able to present an empirical study were included in the literature review. It was initially irrelevant whether this was carried out on a qualitative or quantitative level.

The focus of the study was on the pupils. As already mentioned, this literature review focuses on the influence of simulation-based learning on students. For this reason, studies with other target groups, such as students or teachers, were excluded.

To obtain the broadest possible range of impressions on the topic, no grade levels were excluded. In addition, the country was not an exclusion criterion. Access to full texts is ensured. As the studies were to be analyzed in full, only studies whose full texts were available could be included in the systematic literature review. Attempts were made to obtain the full texts in various ways (library, online databases, universities, and contact with the scientists).

3. Results

It shows the results of the search queries (1309), the selection steps, and the final selection for study analysis (42 publications with 48 sub-studies)

Within some (few) papers, several studies were published, so a total of 48 studies were compared with each other. A detailed tabular analysis of the studies can be found in the article *Simulations in Science Education. A Systematic Literature Review – A detailed insight* from El Tegani & Wegner (2025). A summary of the impact of using simulations in science teaching can be found at the end of the article (Appendix 1).

The results of the literature review show that the use of simulations in science lessons is a topic of great research interest worldwide. The USA, in particular (n=16), Taiwan (n=7), and Germany (n=6) are represented several times in this literature review. In addition to other Western countries such as the Czech Republic (n=4), Denmark (n=3), Finland (n=2), Turkey (n=2), Bosnia and Herzegovina (n=1), Greece (n=1), Spain (n=1) and the UK (n=1), Israel (n=1), Nigeria (n=1), Rwanda (n=1) and Egypt (n=1) are also represented. The studies analyzed simulations both in isolation and comparatively. In general, the use of simulations in science lessons had a positive effect on learners (Barab et al., 2007; Jaakkola et al., 2011; Magana et al., 2019; Shegog et al., 2012). An in-depth analysis shows that four constructs, in particular, were the focus of the studies and were therefore of particular relevance.

3.1. Relevant constructs

Within the scope of the review, several publications revealed consistent research interests and constructs. Performance, knowledge or knowledge gain, self-efficacy, interest, and cognitive load were analysed particularly frequently.

3.1.1. Performance, knowledge and knowledge growth

Several studies compared the students' performance with each other. For example, Ng and Chu (2021) measured the (flight) performance of the students within the simulation. Pucholt (2021) examined the percentage progress in the pre-post test comparison in order to be able to evaluate a change in performance. Other studies looked at performance in the form of a change in knowledge. Eckhardt et al. (2018) also looked at intuitive knowledge. According to the researchers, this special form of knowledge allows the anticipation of possible outcomes in less time than it takes to reflect on the situation (Eckhardt et al., 2018). In this study, simulations appeared to contribute to the intuitive increase in knowledge.

In particular, studies in physics (Cayvaz et al., 2020; Ndihokubwayo et al., 2020; Pucholt, 2021) and chemistry (Olakanmi, 2015; Urhahne et al., 2009) used standardized tests to evaluate knowledge, while studies in biology did not. The reasons for this could not be clearly determined. Several studies showed that simulations can increase the performance and knowledge growth of students (Bílek et al., 2018; Caglar et al., 2015; Chang, 2017; C. Chen et al., 2016; Eckhardt et al., 2013, 2018; H. Liu and Su, 2011; Ndihokubwayo et al., 2020; Ng and Chu, 2021; Olakanmi, 2015; Price, 2013; Tapola et al., 2013; Thisgaard and Makransky, 2017; Zendler and Greiner, 2020). A long-term increase could not be confirmed. Ndihokubwayo et al. (2020) found that both the students who worked with simulations and the students who used videos performed significantly better than the students in conventional lessons with book, chalk, and blackboard (Ndihokubwayo et al., 2020, p. 256). Gelbart et al. (2009) also showed that the simulation group performed significantly better than the control group (book-based lessons). Ng and Chu (2021) concluded in their study that motivation had a positive influence on the students' (flight) performance. Cayvaz et al. (2020) investigated how the choice of medium (book or simulation) affected knowledge as well as scientific thinking and working methods in the context of physics. Students in the simulation group performed significantly better than their comparison group.

The influence of prior knowledge on other variables has also been the subject of research in several studies. For example, Magana et al. (2019) demonstrated that prior knowledge and conceptual understanding can be more beneficial in generating inherent heuristics than pre-existing knowledge that contains erroneous preconceptions. Urhahne et al. (2009) found that students' prior knowledge was strongly associated with their chemistry grades and self-concept, which represents their self-assessment of performance or attributes. Liu and Chuang (2011) found in their study that prior knowledge had a significant impact on household wiring performance. Similarly, Tapola et al. (2013) identified students' prior knowledge as a significant predictor of students' performance. This statement contrasts somewhat with the work of Magana et al. (2019), who identified prior knowledge as a hindering factor in the construction of new knowledge. López and Pintó (2017) pointed out that prior knowledge can play a role in assigning the meaning of scientific objects, so when designing and evaluating simulations, it should first be ensured that the students interpret the presentation correctly. The use of simulations in science lessons, therefore, appears to have a positive influence on students' performance and knowledge growth. In some cases, the simulation as a medium even performed better than alternative media such as a book or a video.

3.1.2. Self-efficacy

According to Bandura (1977), self-efficacy as a construct represents the "belief that one can successfully perform the behavior required to achieve the outcome" (p. 193). Lent et al. (1994; 2000) were able to show that self-efficacy, in particular, can be a strong predictor of a successful career. Several studies found increased self-efficacy after the intervention. (Makransky et al., 2020; Ng and Chu, 2021; Reilly et al., 2021; Thisgaard and Makransky, 2017) The findings of Ng and Chu (2021) with 345 subjects suggest that high self-efficacy is positively influenced by intrinsic and extrinsic motivation and favored by peer support. Reilly et al. (2021) and Makransky et al. (2020) found in their studies that self-efficacy could be significantly increased by working in the (immersive) simulation environment. Thisgaard and Makransky (2017) found that the group that had carried out the simulation first and then the traditional lessons had higher self-efficacy than those who had learned in the reverse order. The use of simulations can also have a positive influence on self-efficacy, although the order of the intervention may also be relevant.

3.1.3. Interest

Interest has also been analyzed in some studies. While Krüger et al. (2022) found no differences in emotional interest between the two groups when comparing simulation and experiment in their study, epistemic and value-related situational interest decreased in the simulation group in both studies. Reilly et al. (2021) also recognized that interest in science was lower after working with the simulation than before. Bílek et al. (2018) were unable to identify any influence of the students' performance on their interests. This contrasts with the findings of Makransky et al. (2020) and Thisgaard and Makransky (2017), who found a significant increase in situational interest in laboratory work and safety (Makransky et al., 2020) and biology (Thisgaard and Makransky, 2017) in their samples in a pre-post comparison. In addition, it was shown that situational interest depends on the increasing concreteness of the simulation and that interest does not have to be a predictor of performance (Tapola et al., 2013).

3.1.4. Cognitive Load

The Cognitive Load Theory (CLT) developed by Paas and Van Merriënboer (1994) is based on the assumption that a cognitive system can only cope with a limited load. An increased cognitive load is generally viewed negatively, as it ties up resources that are no longer freely available for mastering a task (Klepsch, 2020). The exception is the germane cognitive load, which is seen as conducive to learning. (Klepsch, 2020) Based on modern CLT, simulations should ensure simple and accessible presentation and handling so that students have the capacity to engage with the actual subject matter. Krüger et al. (2022) found a higher cognitive load in the students after using the simulation than in the comparison group, in which real experiments were used. Liu and Su (2011) also found a higher cognitive load in the simulation group when comparing the group with the simulation and the virtual lab, and the group with traditional lessons and a subsequent real lab. Krüger et al. (2022) found in their two studies that the cognitive load was significantly higher in the simulation group than in the comparison group in the real-life experiment. Urhahne et al. (2009) and Liu and Chuang (2011) were unable to identify any differences between the groups with different forms of instruction or presentation in terms of cognitive load. Eckhardt et al. (2013) investigated in their studies how the (partial) provision of solutions in simulation-based work affected the cognitive load of the students, among other things. In their study, they found a lower cognitive load when the solutions were not given by the teachers or the simulation but had to be created by the students themselves or generated with support. Li et al. (2022) did not find any differences in the performance of the two groups when they asked whether the order of project-based work and simulation played a role. Eckhardt et al. (2018) investigated scaffold methods in simulation-based learning, with the groups that were able to choose from predefined solutions performing significantly better than those who had to create solutions using, for example, sentence starters or without any help at all.

4. Discussion

Although the results of the literature review make an important contribution to the findings on the topic of "simulations in science lessons", the statements must be assessed subject to a number of limitations. The comparative interpretation of the included studies poses an additional challenge, as the research settings of the studies vary greatly. While some studies in a pre-post design considered simulation as the only treatment in isolation (Dickes et al., 2019; Magana et al., 2019; Ng and Chu, 2021; Reilly et al., 2021; Rosenberg and Lawson, 2019), other researchers conducted comparative studies. The studies also differed greatly in their comparative research settings. Simulation and real-life experiments were compared several times (Eskrootchi and Oskrochi, 2010; Jaakkola et al., 2011; Krüger et al., 2022; Pucholt, 2021; Zendler and Greiner, 2020), while other studies compared simulation with other digital media such as videos (Chang, 2017; Garneli and Chorianopoulos, 2018; Makransky et al., 2020). Others compared simulation-based learning with traditional teaching (Gelbart et al., 2009; Olakanmi, 2015; Thisgaard and Makransky, 2017). The latter represents a specialty with regard to their research setting, as they not only compared simulation with traditional teaching but also evaluated how the order of the interventions (simulation, traditional teaching) affected other dependent variables. They found that the group that went through the simulation first had a higher level of self-efficacy than the comparison group. With regard to the theory of self-efficacy of Bandura (1977), it suggests that working with the simulation either enables more frequent successes or that failures can be quickly replaced by successes. In addition, a simulated environment could have a less intimidating effect on students, as there is less danger that incorrect operation will be immediately penalized during (virtual) experimentation or that equipment will be irreparably damaged. The ability to simply restart the simulation clearly distinguishes the real experiment from the simulation

The work of Blikstein et al. (2016) deserves special mention. In this study the researchers used another attempt to integrate simulation in science Education. The aim of this study was to investigate on supporting students' learning by using a combination of physical experimentation and virtual modeling. This approach is embedded in the *bifocal modeling framework (BMF) (Blikstein, 2016).* With the *bifocal modeling framework* approach, they attempted not to contrast experiment and simulation competitively but rather designed a setting in which the students used the simulation and the experiment simultaneously to gain deeper insights into natural processes. In parallel to the physical experiments, the students were asked to develop virtual models that would replicate the object of investigation as accurately as possible (Blikstein et al., 2016). Even though BMF is open to different tools and phenomena, every modality had three assignments: Design, where the research question was selected, observation was planned and virtual model was planned; Construct where the physical experiment and virtual model was structured and Interact, where they conducted the experiment and changed variables in their model for better fitting (Blikstein, 2016).The iterative comparison of the model data with the real measured data led to a continuous refinement of the models and, therefore also to a better understanding and more realistic ideas of the students (Blikstein et al., 2016). In the presented study the students examined the growing behavior of bacteria. They navigated between macro- and micro-levels of the phenomena. Therefor they translated complex physical phenomena into simple micro-levels (Blikstein, 2016). Every students' project Through their work, the researchers show that a combination of real-life experiment and simulation can be both possible and conducive to learning.

The findings on *prior knowledge* show ambiguous implications for the influence of *prior knowledge* on expected *performance*. While some research could not find any influence in the *learning success* (Zendler & Greiner (2020), other research could find a positive (Liu & Chang, 2011; Tapola et al., 2013; Urhahne et al., 2009) but also negative effects on *knowledge gain* (Magana et al., 2019). Magana et al. (2019) found in their study that children who had little to no prior knowledge of energy efficiency and design (naïve heuristic group, Group 1) showed greater knowledge gain than children who had already achieved a medium to high score in the pre-test (semi-knowledgeable heuristic group; Group 2). In their opinion, there are several possible reasons for this. On the one hand, it could be that the children in Group 2 felt more confident in their actions due to their prior knowledge and therefore did not see the need to delve deeper into alternative solutions, meaning that they were unable to understand the concepts and thus achieved fewer improvements. Rather, the results suggest that the students focused more on cost efficiency than on energy efficiency. The researchers see this as an advantage for group 1, as they invested more time in understanding and asked questions due to their lack of knowledge. However, other reasons could also be ceiling effects or the fact that group 2 had too little time to attempt complex tasks, as the step from average to high requires a deeper conceptual understanding. Although the argumentation of Magana et al. (2019) that new *knowledge* can be anchored more easily and quickly in a less *preloaded environment* seems quite conclusive, the logic of López and Pintó (2017) is also comprehensible against the background of CLT, especially in combination with the findings of Liu and Chuang (2011) and Tapola et al. (2013). The review has shown that there is still a need for further research to investigate the role of *prior knowledge* in terms of *knowledge growth* and *performance* in more detail. It, therefore, makes sense in terms of the DBR to include *prior knowledge* as an object of investigation in future research projects.

In addition to the effect of simulations, the external circumstances of learning were also a research interest of some studies. According to modern CLT according to Sweller et al. (2011), the learning environment should create as appropriate a *cognitive load* as possible in order to avoid unnecessarily burdening the capacities for dealing with the learning object with complicated learning environments and tasks (Klepsch, 2020). Too high a *cognitive load* can lead to excessive demands and thus to poorer *performance* (F. Chen et al., 2016). This is in line with the idea of reducing complexity and difficulty in the spirit of CLT (Sweller et al., 2011). The results of Han and Black (2011) can be interpreted in the opposite way, as in their study, those whose experience showed the highest multimodality, which in the sense of CLT can be interpreted as a *flood of stimuli*, performed best (Han and Black, 2011). However, this must be contrasted with the principle of immersion, which leads to *an immersion* (Mütterlein et al., 2022, p. 248) through a multimodal perception of the simulation, which makes the tasks appear more intuitive, as the interaction no longer takes place between two completely separate systems. To date, there has been a lack of findings in this area on the effect of the joint use of simulation and experiments in science lessons. The use of simulations alongside experiments means a new medium that students have to familiarise themselves with. Further research is needed to examine whether the simulation is perceived as an additional cognitive burden alongside the experiment or whether it represents a relief in terms of scaffolding, as it can better visualize phenomena through didactic reduction and thus make them easier to understand. It makes sense to analyze the *cognitive load* in the research approach in the sense of a comparison of interventions that consider (1) the experiment and (2) the combination of simulation and experiment. With regard to *interest*, the results show no clear implications. Most of the studies presented examined pupils in upper and middle school (Figure 4).

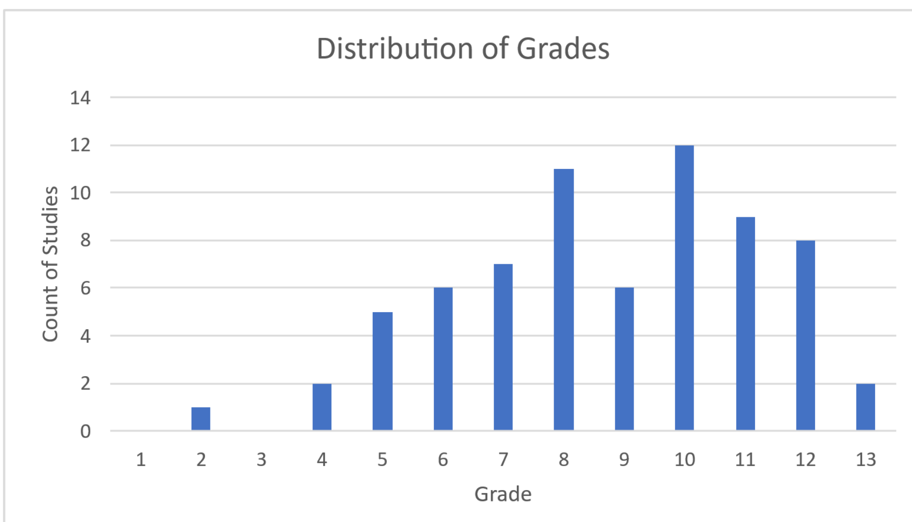

Figure 4. Illustration of how often individual grade levels were represented in the studies. X-axis: grades 1 to 13, y-axis: number of grade levels in which the test subjects were in (multiple answers possible). Studies that did not specify the grade levels are not listed.

The lower grades (grades 5 and 6 in the German school system) and primary school are hardly represented. Gebhard et al. (2017) showed that *interest in science* decreased significantly over the course of lower secondary school. In addition to the problem that biology lessons, for example, are becoming increasingly theoretical and complex, the lack of relevance to the real world is also a reason why pupils become bored with science lessons (Gebhard et al., 2017). This could lead to a vicious circle, as boredom leads to even less interest. This could be counteracted by introducing the digital reality of life more strongly into science lessons using simulations and by achieving a higher degree of interaction between the learning object and the students through simulation-based work, thus enabling practical work.

Under the right conditions, current *situational interest* can promote the development of more stable *individual interest.* In order to increase interest in the subject matter, simulations should receive as much subjective appreciation as possible from the students, and learning with simulations should be an emotional experience. In addition, the work with the simulation should aim to maintain the learners' interest for a certain period of time. This can be achieved, for example, through a varied but not too complex interface (Tolentino et al., 2009) and immersive, multimodal, and interesting storytelling (Han and Black, 2011; Makransky et al., 2020). However, this requires an incentive bond, which in turn provokes acts of interest and thus creates *individual interest.* Motivational factors, such as the need to experience competence, social integration, and autonomy, play an important role here (Gebhard et al., 2017). Tapola et al. (2013) investigated the influence of concreteness on *performance*, *situational interest,* and *interest in maths*. They also attempted to identify predictors of *performance*. *Interest* could not be identified as a predictor of achievement. This contradicts previous research, which has repeatedly found a strong correlation between *interest* and *achievement* (Harackiewicz et al., 2016; Krapp et al., 1993). This is an important finding, which should be part of further research. In view of the diverse subjects in the STEM sector, it should also be examined whether the influence on (subject) interest through the use of simulations depends on the subject. It should be borne in mind that simulations are strongly application-oriented and that a comparison across subjects is a challenge that must be put into perspective.

With regard to *self-efficacy*, the studies reviewed by Ng and Chu (2021), Reilly et al. (2021), Makransky et al. (2020), and Thisgaard and Makransky (2017) imply that simulation-based work can increase *self-efficacy.* In terms of *Social Cognitive Career Theory* (SCCT), promoting *interest in the natural sciences* and increasing *self-efficacy* is expedient in addressing the underlying problem of the shortage of skilled workers in the STEM sector.

5. Recommendations for educational practitioners

The studies considered in this review cover a wide range of application methods and subjects. Nevertheless, connecting elements and effects can be observed that support the use of simulations in science education. Concerning the use of simulations, the authors of this review recommend the following:

1. Ensure that the simulation is precisely integrated into your lesson. It must always be clear where references to the real world and the lesson topic can be made.
2. The use of simulations can increase cognitive load and thus potentially harm learning performance. Therefore, design your tasks and materials in such a way that they introduce the simulation step by step. Also, give students room to experiment. This will take some of the pressure off the actual work phases.
3. Simulations should not replace real experiments if possible, but should be used as a supplement. A co-constructive approach such as that pursued by Bilek et al. (2016) can strengthen both the students' subject knowledge and their modeling skills.
4. In relation to the previous point, however, simulations can certainly be used as a “safe preliminary experiment” to establish the theoretical foundations and increase students' self-efficacy in approaching a topic practically and experimentally.
5. You don't have to reinvent the wheel. Studies show that there are already a variety of simulations on the market. Make use of these and adapt the materials to suit your learning group.

6. Prior knowledge can be helpful but should not prevent one from approaching a topic with an open mind and in depth. Make sure that the tasks are adapted to all learning levels and differentiate where possible.

Conclusion

The literature review has shown that although *self-efficacy* is increased by simulation-based work, no clear statements can be made about the influence of simulation-based work on *interest*. There is a research desideratum here that future research projects should address. The literature review was also unable to make any statements about the effects of combining simulation and experiments in science lessons. Simulations can, therefore, represent added value for science lessons. Nevertheless, their potential is not yet fully utilized in the German school system. A study by Mußmann et al. (2021) showed that only special software, such as simulations, was used in lessons by only six to 35 percent of the teachers surveyed. Their use was strongly dependent on their self-assessed TPACK skills, citing the lack of pedagogical concepts as another reason for the low integration of digital media. They conclude that most technical innovations are made *top-down* by non-school actors and that adequate didactic pedagogical embedding is necessary. This requires resources that professionalize teachers for the operation of the technology and the precise didactic embedding in the classroom (Kabaum and Anders, 2020). To address this problem, project [project name] was founded, in which teachers are to be sensitized and trained in the use of simulations in science lessons through further training. In addition, accompanying research is being carried out to a) identify further reasons for the low use of simulations in science lessons and b) investigate the influence of the training on usage behavior. The aim is to utilize the potential of simulations for science lessons in a reflected manner and to promote German education regarding its digitality.

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Supplementary Information: For deeper insights into the analyzed studies, please use **Appendix 1**, which contains information about their study design and a summary of the results. An even shorter version can be found in, which evaluates the effects of simulation-based learning in the examined constructs.

Appendix 1. Summary of research priorities and effects of the simulation on these (**+** positive, **o** neutral, **-** negative) (continued)

Authors (year)	**Focus of investigation**	**Effect of the simulation (+/o/-)**
Krüger et al. (2022) Study I+II	Comparison of simulation and experiment on expertise / cognitive load/interest	+/+/-
Li et al. (2022)	Sequence of simulation and project-based work	o
Ng & Chu (2021)	Consequences of simulation on the performance of pupils	+
Pucholt (2021)	Comparison of simulation and classical experimental teaching concerning memorization/percentage progress	o/+
Reilly et al (2021)	Influence of simulation on self-efficacy/interest/understanding of causality, correlation	+/+/-
Cayvaz et al (2020)	Comparison of simulation and textbook on knowledge / scientific ways of thinking and working / attitude to science	+/+/o
Makransky et al (2020) Study I	Influence of simulation on interest/self-efficacy / scientific ambition	+/+/o
Makransky et al (2020) Study II	Comparison of simulation and video for interest/self-efficacy / scientific ambition	+/+/+
Ndihokubwayo et. al. (2020)	Comparison of simulation, YouTube videos, and conventional teaching for performance	+
Zendler & Greiner (2019)	Comparison of experiment and simulation on learning success	o
Dickes et al (2019)	Influence of simulation on causal explanations	+
Magana et al (2019)	Influence of simulation-based learning on concept understanding/knowledge	+/+
Rosenberg & Lawson (2019)	Influence of simulation on conceptual understanding	+
Bilek et al. (2018)	Influence of simulation on interest/performance	o/+
Correia et al (2018)	Influence of simulation on attitude / conceptual change	+/+
Eckhardt et al. (2018)	Influence of various supports on the increase in knowledge and self-assessment	+/+
Garneli & Chorianopoulos (2018)	Influence of video games and simulation design on computational thinking and motivation	+/+
Wen et al (2018)	Influence of simulation on modelling skills	+
Yoon et al (2018)	Influence of different scaffold methods on understanding/perception	+/+
Chang (2017) Study I	Comparison of simulation and observation in terms of learning time, result, number of trials, and learning efficiency	+/o/o/o
Chang (2017) Study II	Influence of question format on learning time, result, number of attempts and learning efficiency	+/o/+/+

López & Pintó (2017)	Difficulties in reading and understanding simulations	o
Thisgaard & Makransky (2017)	Comparison of the sequence of simulation and traditional teaching and effect on knowledge gain, self-efficacy, motivation, interest and expected results	+
Blikstein et al. (2016)	Use of "bifocal modelling"	+
Chen et al. (2016)	Influence of the scale fidelity of simulated models on performance	+
Caglar et al. (2015)	Impact of web-based simulation on learning gains in computational thinking and scientific understanding	o
Mešić et al. (2015)	Influence of teaching method (simulation, pictures, diagram) on attitude and understanding	+/+
Olakanmi (2015)	Comparison of web-based simulation and traditional analogue teaching in terms of performance and attitude towards chemistry	+/+
Eckhardt et al. (2013)	Effect of solution and reflection support on knowledge gain and cognitive load in simulations	+/+
Price (2013)	Comparison of simulation and overhead projector in terms of performance (percentage improvement)	+
Tapola et al. (2013)	Influence of the concreteness of the conditions and students' prior knowledge on performance and interest in math	+
Lin et al. (2012)	Influence of simulation on research expertise and knowledge	+/+
Shegog et al. (2012)	Comparison of dual simulation and homework and simulation on procedural and declarative knowledge / attitude towards the use of computers / manageability of the program	+/+/+
Han & Black (2011)	Influence of multimodal representation of a simulation on the ability to adapt and create multimodal representations / on the knowledge of mechanisms of simple machines	+/+
Jaakkola et al. (2011)	Influence of the environment (simulation, simulation+ lab) and the explicitness of the instruction on subjective knowledge, learning time and learning efficiency	+/+/+
Liu & Chuang (2011)	Influence of instructions on cognitive load, performance and cognitive efficiency	+
Liu &Su (2011)	Influence of the learning environment (simulation+ virtual lab, traditional teaching + real lab) on performance and cognitive load	+/+
El-Sabagh (2011)	Influence of a web-based virtual laboratory on conceptual understanding / scientific methodological competences	+/+
Eskrootchi & Oskrochi (2010)	Comparison of project-based, project-based experimental and project-based simulated teaching on content knowledge / understanding / attitude towards the project	o/-/+
Gelbart et al. (2009)	Comparison of simulation and standard lessons on understanding / explanatory ability	+/+
Tolentino et al. (2009)	Influence of simulation on conceptual knowledge / spatial rotational thinking	+/+
Urhahne et al.	Comparison of 3D simulation and 2D image on	+/o

(2009)	conceptual knowledge / factual knowledge	
Barab et al. (2006)	Influence of simulation on performance / understanding	+
Henderson et al. (2000)	Influence of simulation on skills	+

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