



The learning effects of computer simulations in science education

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ABSTRACT

This article reviews the (quasi)experimental research of the past decade on the learning effects of computer simulations in science education. The focus is on two questions: how use of computer simulations can enhance traditional education, and how computer simulations are best used in order to improve learning processes and outcomes. We report on studies that investigated computer simulations as a replacement of or enhancement to traditional instruction. In particular, we consider the effects of variations in how information is visualized, how instructional support is provided, and how computer simulations are embedded within the lesson scenario. The reviewed literature provides robust evidence that computer simulations can enhance traditional instruction, especially as far as laboratory activities are concerned. However, in most of this research the use of computer simulations has been approached without consideration of the possible impact of teacher support, the lesson scenario, and the computer simulation's place within the curriculum.

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1. Introduction

The increasing availability of computers and related equipment such as smartboards and mobile devices, as well as the fact that computer simulations have become available for a wide range of science subjects (e.g., the *PhET sims* at <http://phet.colorado.edu>, 2011), have led to simulations becoming an integral part of many science curricula. This raises the question of how simulations are best used to contribute to improved learning of science. Research into the use of computer simulations has a long history, as *de Jong and van Joolingen* (1998) pointed out in their review. In the present review, we investigate the state of the art in simulations for science education, focusing on the ways simulations can be used to enhance traditional instruction and on the ways they can be embedded in instructional support to promote learning processes. We determined the reported effects of those interventions on learning process and learning outcome.

According to *de Jong and van Joolingen* (1998) a computer simulation is “a program that contains a model of a system (natural or artificial; e.g., equipment) or a process”. Their use in the science classroom has the potential to generate higher learning outcomes in ways not previously possible (*Akpan*, 2001). In comparison with textbooks and lectures, a learning environment with a computer simulation has the advantages that students can systematically explore hypothetical situations, interact with a simplified version of a process or system, change the time-scale of events, and practice tasks and solve problems in a realistic environment without stress (*van Berkum & de Jong*, 1991). A student's discovery that predictions are confirmed by subsequent events in a simulation, when the student understands how these events are caused, can lead to refinement of the conceptual understanding of a phenomenon (*Windschitl & Andre*, 1998). Possible reasons instigating teachers to use computer simulations include: the saving of time, allowing them to devote more time to the students instead of to the set-up and supervision of experimental equipment; the ease with which experimental variables can be manipulated, allowing for stating and testing hypotheses; and provision of ways to support understanding with varying representations, such as diagrams and graphs (*Blake & Scanlon*, 2007).

By placing emphasis on the learner as an active agent in the process of knowledge acquisition, computer simulations can support authentic inquiry practices that include formulating questions, hypothesis development, data collection, and theory revision. Proceeding through a simulation can gradually lead learners to infer the features of the simulation's conceptual model, which may lead to changes in the learners' original concepts (*de Jong & van Joolingen*, 1998). By actively involving learners in exploring and discovering, computer simulations

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can be powerful learning tools, as learning involving *doing* is retained longer than learning via listening, reading, or seeing (Akpan, 2001). Even though the tendency toward more learner-centered instead of teacher-centered education has caused this *discovery learning* approach to be popular (Veermans, van Joolingen, & de Jong, 2006), the extent to which control can be turned over from the teacher to the learner does have its limits. If there is insufficient support for the processes of discovery learning within a computer simulation, learners have difficulties in generating and adapting hypotheses, designing experiments, interpreting data and regulating learning (de Jong & van Joolingen, 1998). Minimization of guidance clearly leads to a deterioration of the effectiveness of inquiry learning. Even though providing learning support restricts the students' possibilities of freely exploring the simulation environment to a certain extent, the scaffolding it provides improves their performance in simulation-based learning (van Berkum & de Jong, 1991).

In recent years learning technologies have lost their initial prestige, because they were often introduced with mythical overstatements regarding their effects on learning processes and outcomes, and were subsequently unable to live up to those expectations (Dillenbourg, 2008). What does research of the past decade on computer simulations in science learning say about their educational effectiveness in this regard? Is their application advisable and is their effectiveness –as far as their use as pedagogical intervention is concerned– robust?

Our investigation of interventions considered in the research on educational computer simulations in science learning first endeavored to cluster the themes of those interventions into categories. Subsequently, we examined whether the effectiveness of computer simulations from the perspective of those themes could be deduced from the research. In other words, the present study focuses on answering the following research questions:

- How can traditional science education be enhanced by the application of computer simulations?
- How are computer simulations best used in order to support learning processes and outcomes?

We were also interested in the extent to which researchers considered the role of teachers in guiding the students' learning processes while working on the simulation.

Our categorized themes are based on the results of our literature search and serve merely as a possible way of organizing these results. Therefore, we certainly do not claim this categorization to be comprehensive. However, a clearer picture of the effectiveness of computer simulations from the perspective of these themes can serve as a basis for deriving teacher guidelines for providing effective guidance to students while working with computer simulations.

2. Method

2.1. Data collection

To answer the research questions, three databases were searched for relevant research articles: ERIC (2011), Scopus (2011) and ISI Web of Knowledge (2011). Searching these databases started on September 21st, 2009 and was repeated to track changes until the final check on April 14th, 2011. We limited our search to the past decade (published in the period 2001–2010). *Journal articles* and *reviews* were searched by using the following keywords: ["computer simulation" OR "interactive learning environment"], [science OR physics OR chemistry OR biology OR mathematics] and [(education* OR instruction*) AND (teach* OR train*)]. The ERIC-search resulted in 333 articles. The Scopus-search –additionally limited by [Social Sciences OR Psychology]– resulted in 163 articles. The search of ISI Web of Knowledge –additionally limited by [Education & Educational Research OR Psychology OR Behavioral Sciences]– resulted in 89 articles. By comparing the total of 585 publications, we found 75 duplicates. The exclusion of these duplicates resulted in a total of 510 unique publications.

To decide whether publications were actually about computer simulations as we conceive them, we determined whether de Jong and van Joolingen's (1998) definition of *computer simulation* (as stated earlier) applied. We consider the possibility of interacting with a simulation to be an essential characteristic, distinguishing this construct from animations (instructional animations, which have been excellently reviewed by Höffler & Leutner, 2007). We focused on students from 12 to 20 years old, as these are the most important years for the acquisition of basic scientific knowledge. Studies on computer simulations in areas other than science were excluded, except for the other affiliated STEM-disciplines: technology, engineering and mathematics. Studies about modeling were also excluded, as modeling can be considered to be a distinct research area. We are particularly interested in studies in which the computer simulation serves an educational purpose. Therefore, we selected those studies in which the use of the computer simulation is aimed at changing knowledge and/or skills, and in which these changes are quantitatively measured and a comparison between groups and/or between pretest and posttest is made. As our interest in the measurement of learning effects led to our focus to be on (quasi)experimental studies, applying this criterion inevitably led to the exclusion of works that address relevant questions, but do not focus on an empirical intervention, such as research on the Molecular Workbench by the Concord Consortium (Pallant & Tinker, 2004; Tinker & Xie, 2008), and research on the Physics Education Technology (PhET) project (Finkelstein et al., 2005; Finkelstein, Adams, Keller, Perkins, & Wieman, 2006; Wieman & Perkins, 2005, 2006). Studies that merely describe the design of a computer simulation, or use subjective judgment (as in feedback questionnaires) as the only instrument of measurement were excluded. To ensure the quality of the publications, we excluded studies in journals that are not registered in the ISI Web of Knowledge (2011) database. Applying all exclusion criteria left a total of 51 publications remaining, 48 empirical studies and 3 reviews.

2.2. Qualitative analysis

After investigating the contents of each publication, we endeavored to find ways to categorize the studies by looking at coherence between the interventions on which the studies focused. We distinguished the following themes that served to interrelate the interventions addressed across this body of studies: variations in *representation*; degree of *immersion* (the extent to which users of a virtual environment actually believe they are inside this environment); *instructional support*; *gaming*; level of *engagement*; *teacher guidance*; and *collaboration*. Studies that make an overall comparison between using computer simulations and traditional instruction –and therefore focus less specifically on certain themes– are reviewed separately. After having scored each study's intervention accordingly for thematic relatedness,

we concluded that considering *gaming* and *engagement* as separate categories would be unjustified, as these themes are each the focus of intervention in merely two studies. This review is organized according to the remaining themes as grouped under four major categories: *enhancement of traditional instruction with computer simulation* (including the themes *traditional instruction* and *laboratory activities*), different kinds of *visualization* (including *representation* and *immersion*), different kinds of *instructional support*, and *classroom settings and lesson scenario* (including *engagement*, *teacher guidance* and *collaboration*). We distinguish *visualization* from *representation*, as using different media –e.g., stereoscopic glasses and a computer screen– allows for visualizing the same representation in various ways. As long as conditions studied are restricted to the computer screen, we refer to this as a comparison between different representations; as soon as other media are used –e.g., mixed-reality technology– or media differ across conditions we use the term visualizations. Representations displaying processes that change with respect to time, are referred to as being *dynamic* (Ainsworth & VanLabeke, 2004).

2.3. Statistical analysis

Where relevant and possible, effect sizes were calculated. We used the methods of Thalheimer and Cook (2002) for calculating Cohen's *d* from the data presented in the studies. Even though Thalheimer and Cook (2002) offer five different ways of calculating Cohen's *d*, the data from 19 studies did not allow for its calculation, which makes drawing conclusions at a meta-analytic level unwarranted. Among the studies that report an intervention effect (43 studies) reasons for missing *d*'s are: *t*-tests or *F*-tests or data on which these could be based are missing (12); or statistical data are reported only at a detailed level and do not allow for calculation of a *d* that can be associated with the authors' overall conclusions (7).

3. Results

In reviewing the publications all studies were assigned to four major categories, which were subdivided into specific themes: *Enhancement of traditional instruction with computer simulation*, subdivided into *computer simulation and traditional instruction* and *laboratory activities and computer simulation*; *Comparison between different kinds of visualization*, subdivided into *different kinds of representation and varying degrees of immersion*; *Comparison between different kinds of instructional support*, subdivided into *supporting Scientific Discovery Learning and instructional support approached from other perspectives*; and *Classroom settings and lesson scenario*, subdivided into *varying levels of engagement and the roles of teacher guidance and collaboration*. Needless to say, most studies do not focus on just one theme, but rather attempt to take several themes into account. Therefore, our categorization of the studies is based on each study's focal intervention. For example, the studies by Gelbart, Brill, and Yarden (2009), Mitnik, Recabarren, Nussbaum, and Soto (2009), Manlove, Lazonder, and de Jong (2006), and Saab, van Joolingen, and van Hout-Wolters (2007) all take *collaboration* into account, but none of these studies is placed under the category of *collaboration*. This is because while all of these studies work with collaborating students in the experimental group as well as in the control group, they focus their intervention itself on another theme.

3.1. Enhancement of traditional instruction with computer simulation

The 17 studies in this section have in common that they investigated the effects of computer simulations as a supplement or alternative to traditional teaching, as opposed to comparing different kinds of simulations with each other. We first discuss studies that are relatively diverse in their research approach, and then move on to discuss studies that investigated the specific topic of computer simulations in the realm of laboratory activities. Table 1 provides specific details on the studies reviewed in this section.

3.1.1. Computer simulation and traditional instruction

Jimoyiannis and Komis (2001) compared a group of students who received traditional classroom instruction with a group who were exposed to both traditional instruction and computer simulations. They investigated the effect of this intervention on students' understanding of basic kinematics concepts concerning simple motions through the Earth's gravitational field. The students who used the computer simulation in addition to traditional instruction achieved significantly higher results on the research tasks. Therefore, the researchers suggest that computer simulations can be used as a complement to or alternative for other forms of instruction in order to facilitate students' understanding of velocity and acceleration. Stern, Barnea, and Shauli (2008) similarly compared two groups of students, both of which were taught curriculum on the kinetic molecular theory. The experimental group subsequently spent additional class periods using the computerized simulation, "A Journey to the World of Particles". The students in the experimental group scored significantly higher than the students in the control group (Cohen's *d* = 0.81) on a test measuring their understanding of the theory. However, overall achievement was very low and long-term learning differences negligible. The authors attribute this to a lack of sound teaching strategies, i.e., addressing students' prior knowledge, and guiding their interpretations of learning experiences.

The study by McKagan, Handley, Perkins, and Wieman (2009) investigated the effects of reforming a physics course; among other changes, a computer simulation was implemented in the curriculum on the photoelectric effect. As demonstrated by improved exam achievement, the reformed curriculum led to an improved ability to predict the results of experiments on the photoelectric effect. However, students' ability to connect observations and inferences logically did not improve. According to the authors this might be a symptom of students' more general lack of reasoning skills for drawing logical inferences from observations. As the implemented learning techniques were not investigated separately, claims about the effectiveness of computer simulations can hardly be made on the basis of this study.

In comparing a research simulation with regular class work within the domain of genetics, Gelbart et al. (2009) found a significantly positive influence of the computer simulation on learning outcomes. Students' understanding was measured by testing their ability to respond correctly to true/false statements (*d* = 0.87) and to provide explanations for their choices (*d* = 0.80). Moreover, two learning types could be distinguished among the students, based on differences in how they take advantage of opportunities to become conversant with research practices: students who are more research-oriented appear to be more able to expand their knowledge in comparison with more task-oriented students. Riess and Mischo (2010) also assessed the learning effectiveness of a computer simulation by investigating students' task performance as well as their ability to provide explanations for their answers. Students received the task of cultivating a simulated section of forest in order to experience short- and long-term effects of treating a forest as a cultivated ecosystem. Results show that systems

Table 1
Enhancement of traditional instruction with computer simulation.

Primary author (year of publication)	Science discipline	Cognitive topic	N	Interventions	Results/conclusions	Effect size (Cohen's <i>d</i>)
Computer simulation and traditional instruction						
Gelbart et al (2009)	Biology	Genetics	95	Computer simulation vs. regular class work	Better understanding	0.87 (statements) 0.80 (explanations) *
Riess and Mischo (2010)		Ecosystem forest	424	Learning approach: research-oriented vs. task-oriented Simulation and lessons vs. traditional teaching	More knowledge expansion Higher learning gains	0.37 (achievement) 0.13 (justification) 0.21 (justification)
Kiboss et al (2004)		Cell theory	102	Lessons only vs. traditional teaching Computer-Mediated Simulations program vs. traditional teaching	Improved knowledge and performance Improved perception of classroom environment Improved attitude toward the subject	1.54** 2.78** 2.16**
Duran et al (2007)		Electric machinery	± 250	Software-based method vs. traditional teaching	More discussion both among students and with the teacher in a brainstorming stage Higher student satisfaction and more participation and initiative Better understanding	* * *
Jimoyiannis and Komis (2001)	Physics	Trajectory motion	90	Traditional instruction with computer simulations vs. traditional instruction without computer simulations		
Stern et al (2008)		Kinetic molecular theory	133	Traditional instruction with computer simulations vs. traditional instruction without computer simulations	Better understanding in the short term (however, no long-term difference)	0.81
McKagan et al (2009)		Photoelectric effect	47	Computer simulation vs. traditional instruction	Better ability to predict results	*
Laboratory activities and computer simulation						
Gibbons et al (2004)	Biology	Chromosome analysis	Study 1: 47	Virtual approach vs. real approach	Decreased study time	3.56 (practice) 2.36 (assessment)
		Bioinformatics	Study 2: 30		Increased assessment scores	0.71 (topic 1) 0.40 (topic 2)
White et al (2010)	Chemistry	Protein structure	477	Computer simulation vs. visualization	No difference in learning gains	n.a.
Meir et al (2005)		Diffusion	Study 1: 15	Virtual laboratory (pretest-posttest)	Better understanding	*
		Osmosis	Study 2: 31			
Martinez-Jimenez et al (2003)		Caffeine extraction from tea	274	Traditional methods with Virtual Chemistry Laboratory vs. traditional methods without Virtual Chemistry Laboratory Interaction effect: Virtual Chemistry Laboratory AND greatest learning deficiencies	Better comprehension of the techniques and basic concepts Highest improvement	* *
Winberg and Berg (2007)		Acid-base titration	Study 1: 175 Study 2: 58	Computer simulation vs. laboratory exercise	Posing more theoretical questions during laboratory work Exhibiting a more complex, correct use of chemistry knowledge during interviews Better understanding	* * *
Limniou et al (2007)		Viscosity	88	Laboratory with pre-lab simulation exercise vs. laboratory without pre-lab simulation exercise		
Dalgarno et al (2009)		Laboratory familiarization	Study 1: 22 Study 2: 95	Virtual laboratory vs. real laboratory	No difference in effectiveness for gaining familiarity with the laboratory Better academic results and increased interest in the course	n.a. *
Baltzis and Koukias (2009)	Engineering	Analog electronics	518	Laboratory with simulation vs. laboratory without simulation	Better conceptual understanding	0.70
Zacharia (2007)	Physics	Electrical circuits	90	Laboratory with simulation vs. laboratory without simulation		
Chang et al (2008)		Optical lens	Study 1: 153 Study 2: 231	Simulation-based learning vs. laboratory learning	Better learning outcomes	0.12 (prompting) 0.17 (hypothesis menu) 0.11 (step guidance) 0.06
				Abstract reasoning abilities: high vs. low	More benefit from simulation-based learning	
				Experiment prompting OR hypothesis menu vs. step guidance	Better learning results	0.03 (prompt. vs. step) 0.06 (menu vs. step)

Note. All studies are presented in order of discussion in this review, grouped by science discipline. Calculation of Cohen's *d*: n.a. = not applicable; * = not possible, based on the methods by Thalheimer and Cook (2002), ** = equal group sizes assumed.

thinking can be most effectively fostered by providing a combination of specific lessons and opportunities to explore a computer simulation ($d_{\text{achievement}} = 0.37$ and $d_{\text{justification}} = 0.13$).

In their study, Duran, Gallardo, Toral, Martinez-Torres, and Barrero (2007) focused on both the affective and cognitive domains in order to investigate the effects of a computer simulation on students' motivation and interaction. They replaced part of the traditional method in a subject titled "Electrical Machines and Installations" with a software-based method that made use of a computer simulation. This appeared to stimulate discussions among the students themselves as well as with the teacher during the brainstorm session. Although the results for the cognitive domain could not be clearly interpreted, the results for the affective domain indicate that the new method has a profound influence on student satisfaction. The authors ascribe this improvement to the use of real-world examples and showing real-time simulations during lectures. Additionally, the new method improves participation and students' initiative compared to traditional instruction. We will elaborate further on this study in Section 3.4.2.. The study by Kiboss, Ndirangu, and Wekesa (2004) similarly took both cognitive and affective gains into account. Their Computer-Mediated Simulation program on the biology subject of cell theory led to improvements in academic achievement ($d = 1.54$), students' perceptions of classroom environment ($d = 2.78$), and their attitudes toward the subject ($d = 2.16$, all very large effects).

3.1.2. Laboratory activities and computer simulation

Multiple studies focused on using simulations as a means of preparing students for laboratory activities. In the study by Martinez-Jimenez, Pontes-Pedrajas, Polo, and Climent-Bellido (2003), students in both the control and experimental groups performed an experiment on the extraction of caffeine from tea. A pre-laboratory simulation program introduced the experiment for the experimental group. Student performance was evaluated for: carrying out the experiment, laboratory report quality, experiment problem-solving and results of a written test. The researchers found that using the preparatory simulation leads to better comprehension of the techniques and basic concepts used in their laboratory work. The students with the greatest learning deficiencies profit most from using the pre-laboratory program. In a study by Baltzis and Koukias (2009), students taking a course on analog electronics were encouraged to complete a circuit simulation task individually prior to performing a laboratory experiment in pairs. This intervention led to increased interest in the course and an overall improvement of academic performance.

Another study on pre-laboratory exercises was conducted by Winberg and Berg (2007), who considered the questions that students ask their teachers during the laboratory exercise as an indicator for cognitive focus, and took the spontaneous use of chemistry knowledge during interviews as an indicator of the usability of knowledge. The results of their experiments suggest that introducing laboratory work with a preparatory computer simulation leads to students asking more theoretical questions during laboratory work and showing more chemistry knowledge while being interviewed. The authors therefore conclude that preparatory exercises intended to help students integrate their theoretical, conceptual knowledge into schemata can allow room for reflection, but may also contribute to students having a better sense of direction during their laboratory work. In a similar fashion, Limniou, Papadopoulos, Giannakoudakis, Roberts, and Otto (2007) show that replacing part of a laboratory session on the topic of viscosity with a collaborative pre-lab simulation exercise can improve content knowledge.

In a more recent study, Dalgarno, Bishop, Adlong, and Bedgood (2009) compared the ability of a 3-dimensional Virtual Laboratory (VL) and a Real Laboratory (RL) to function as a tool for familiarizing students with the spatial structure of a laboratory and the apparatus and equipment it contains. After the VL-group had explored the simulation (see Fig. 1) and the RL-group had been taken on a tour of the actual laboratory, all students were tested on their recall of the laboratory layout and their familiarity with apparatus. The researchers conclude that the Virtual Laboratory is an effective tool for familiarization with the laboratory setting.

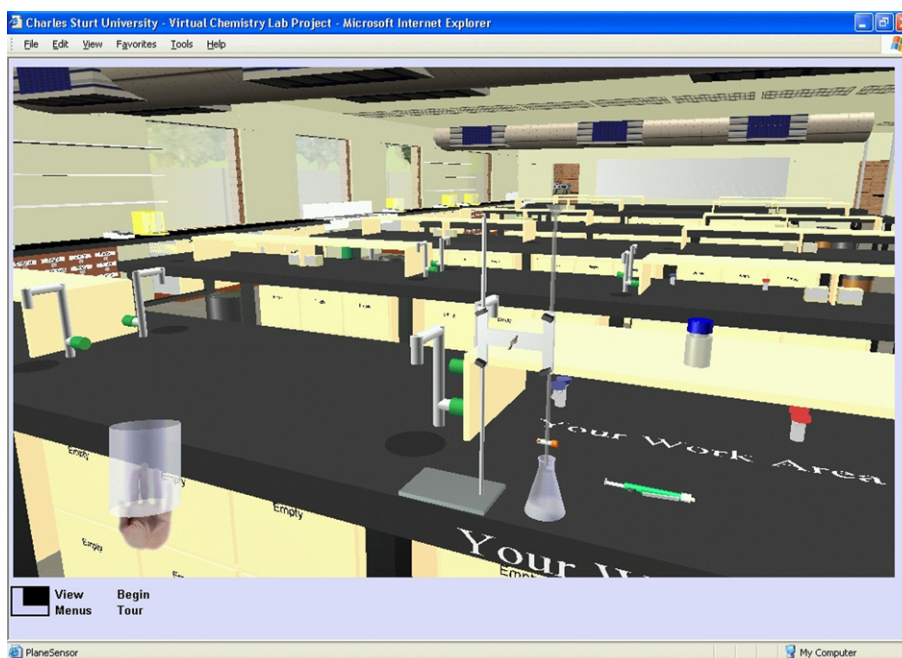


Fig. 1. The Virtual Chemistry Laboratory studied by Dalgarno et al. (2009). Printed with permission.

In studying the differences between using so-called *Real Experimentation* (RE) and *Virtual Experimentation* (VE), Zacharia (2007) compared a control group only using RE with an experimental group using a combination of RE and VE (see Fig. 2). The results indicate that replacing RE with VE during a specific part of the experiment has a positive influence on students' conceptual understanding of electrical circuits, as measured by conceptual tests ($d = 0.70$). The effectiveness of virtual laboratories versus real laboratories as learning mechanisms has also been investigated by Gibbons, Evans, Payne, Shah, and Griffin (2004) in a bioinformatics class. Based on their first study, they assert that virtual laboratories can save significant amounts of time for students without affecting learning ($d_{\text{practice}} = 3.56$ and $d_{\text{assessment}} = 2.36$, both very large effects on study time, where *practice* and *assessment* respectively refer to exercises with and without immediate feedback). In their second study they found that virtual laboratories do not necessarily lead to performance improvements: the potential of virtual laboratories to outperform traditional laboratories depends on the nature of the presented material ($d_{\text{topic 1}} = 0.71$ and $d_{\text{topic 2}} = 0.40$). In a study on the topic of protein structure, White, Kahrman, Luberic, and Idleh (2010) compared traditional teaching with a 3D visualization and a simulation that shows the consequences for protein folding of altering amino acid sequences. The authors conclude that the learning effectiveness of their visualization and simulation activities is comparable, and that these activities are more effective than traditional instruction. Meir, Perry, Stal, Maruca, and Klopfer (2005) investigated another virtual laboratory called OsmoBeaker, which allows students to perform inquiry-based experiments on diffusion and osmosis at the molecular level. Even though their simulated laboratories lead to improved understanding and can help to overcome student misconceptions, the authors emphasize the key role that written instructions accompanying the simulations play in promoting learning, as simply presenting a simulation environment to students is not enough.

Chang, Chen, Lin, and Sung (2008) compared using computer simulations with traditional laboratory learning, as well as different supportive learning models with each other. They also investigated whether abstract reasoning abilities would have an impact on the extent to which students could learn from simulations. The results show that learning about optical lenses by using simulations leads to a significantly greater improvement in learning outcomes in comparison with traditional laboratory practice (although all effect sizes are small: $d_{\text{experiment prompting vs. lab}} = 0.12$, $d_{\text{hypothesis menu vs. lab}} = 0.17$ and $d_{\text{step guidance vs. lab}} = 0.11$). Students with better abstract reasoning abilities appear to benefit more from simulation-based learning ($d = 0.06$, a negligible effect). The authors conclude that helping students with the construction of hypotheses is a good way to support simulation-based learning in general. However, they warn that the offering of support during experimental procedures limits the students' freedom insofar as they are to follow the offered steps, which can weaken their learning results.

3.1.3. Summary and discussion

The reviewed studies that compared the application of computer simulations with traditional instruction seem to indicate that traditional instruction can be successfully enhanced by using computer simulations. Within traditional education they can be a useful add-on, for example serving as a pre-laboratory exercise or visualization tool. In most cases simulation conditions showed improved learning outcomes, with effect sizes up to 1.54. With regard to the cognitive domain, use of computer simulations appears to facilitate students' conceptual understanding (Jimoyiannis & Komis, 2001; Meir et al., 2005; Stern et al., 2008; Zacharia, 2007), requires less time (Gibbons et al., 2004), and improves the ability to predict the results of experiments (McKagan et al., 2009). With regard to the affective domain, computer simulations can positively influence students' satisfaction, participation and initiative (Duran et al., 2007) and improve their perception of the classroom environment (Kiboss et al., 2004). Studies that specifically focused on using computer simulations as pre-laboratory exercise tools conclude

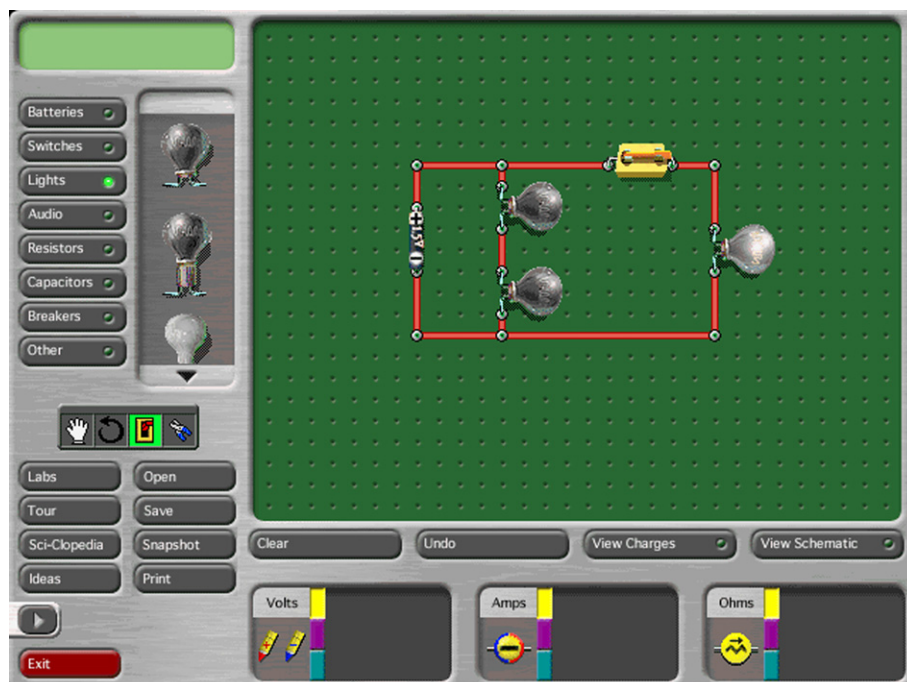


Fig. 2. The Virtual Laboratories Electricity environment studied by Zacharia (2007). Printed with permission.

that they can effectively support familiarization with the laboratory (Dalgarno et al., 2009), improve students' cognitive focus (Winberg & Berg, 2007), lead to better comprehension of the techniques and basic concepts used in laboratory work (Martinez-Jimenez et al., 2003), and increase interest in the course and improve academic results (Baltzis & Koukias, 2009; Limniou et al., 2007). Martinez-Jimenez et al. (2003) additionally report that those students with the greatest learning deficiencies profited most from working with the pre-laboratory program.

The results of research on the enhancement of traditional instruction with computer simulation are promising, as the majority of studies report improvements for the cognitive and affective domains. However, a word of caution is warranted, as short-term increased understanding does not necessarily lead to meaningful learning over the long term –as Stern et al. (2008) point out– and most studies in this category investigated only short-term results. In order to ensure that meaningful learning takes place, it is necessary to attune teaching strategies and the curriculum to the use of simulations and vice versa (Stern et al., 2008), as by the encouragement of students to follow a research-oriented approach (Gelbart et al., 2009) or by focusing curriculum on the development of scientific reasoning skills (McKagan et al., 2009).

3.2. Comparison between different kinds of visualization

Beyond studying whether computer simulations can enhance traditional instruction, many researchers focused their attention on the question of how to implement a computer simulation. Studies addressed issues including ways of visualizing simulation processes, specific support measures, and configurations of the classroom setting and lesson scenario. In this Section 7 studies that compare different kinds of visualizations are reviewed. We begin by discussing variations in representation and continue with varying students' degree of immersion by using different media. Table 2 provides specific details on the studies reviewed in this section.

3.2.1. Different kinds of representation

In an investigation of whether students' understanding of line graphs could be improved by means of dynamic representations, Ploetzner, Lippitsch, Galmbacher, Heuer, and Scherrer (2009) compared groups that varied in the availability of simulated motion phenomena, dynamic line graphs, dynamic iconic representations and dynamic stamp diagrams. In an initial study, students appeared to be unable to make use of the dynamic representations for improving their understanding of line graphs. As the researchers hypothesized that the lack of effectiveness was caused by insufficient support, they performed a second study in which they complemented the design of dynamic representations with pedagogical measures: during learning students could have their questions clarified, as they could ask questions and receive assistance from a teacher as well as from peers. Combining representations with supportive pedagogical measures led to more successful learning than dynamic representations alone.

Table 2
Comparison between different kinds of visualization.

Primary author (year of publication)	Science discipline	Cognitive topic	N	Interventions	Results/conclusions	Effect size (Cohen's <i>d</i>)
Different kinds of representation						
Trey and Khan (2008)	Chemistry	Le Châtelier's Principle	15	Computer simulation with dynamic analogy vs. computer simulation without dynamic analogy	Enhanced learning of unobservable phenomena in science	1.45**
Goldstone and Son (2005)	General science	Competitive specialization	Study 1: 84	Concreteness fading OR concreteness introduction vs. consistently idealized OR consistently concrete	Better performance on the simulation itself	0.65 (1) & 0.58 (2)
			Study 2: 88	Concreteness fading vs. concreteness introduction	Better transfer to another simulation Better performance	0.86 (1) & 0.66 (2) *
Ploetzner et al (2009)	Physics	Kinematics	Study 1: 111 Study 2: 24	Dynamic visualizations with pedagogical measures vs. dynamic visualizations without pedagogical measures	Improved understanding of line graphs	*
Varying degrees of immersion						
Moreno and Mayer (2004)	Biology	Botany	48	Personalized agent messages vs. nonpersonalized agent messages	Better performance on retention and problem-solving tests	0.94 (retention) 1.79 (problem-solving)
				Immersion: head-mounted display vs. desktop delivery	Higher reported level of physical presence, but no difference in performance on tests of retention and transfer	n.a.
Trindade et al (2002)	Chemistry	Molecular dynamics and atomic orbitals	20	3D virtual environment visualization with stereo glasses vs. 3D virtual environment visualization on screen	More immersion, but not much contribution to conceptual understanding	*
Birchfield and Megowan-Romanowicz (2009)	Earth science	Geologic evolution	72	Mixed-reality learning environment (pretest-posttest)	Increased student discussion exchanges and increased test scores	*
Mitnik et al (2009)	Physics	Kinematics	23	Robotic vs. computer-simulated	Better graph interpreting skills, higher motivation and more collaboration	1.14 (skill)

Note. All studies are presented in order of discussion in this review, grouped by science discipline. Calculation of Cohen's *d*: n.a. = not applicable; * = not possible, based on the methods by Thalheimer and Cook (2002); ** = equal group sizes assumed.

Trey and Khan (2008) paid special attention to using computer-based analogies to simulate unobservable scientific phenomena. Two groups of students were introduced to a computer simulation on chemical equilibrium behavior. The simulation shows a dynamic analogy of Le Châtelier's Principle on the stability of equilibrium situations. During the simulation one of the groups worked with the simulated analogical example; students in the other group were asked to recall a verbal and pictorial static analogy presented in the form of text and pictures, which both groups had seen earlier. The results suggest that analogies that are dynamic, interactive and integrated in a computer simulation can have a stronger effect on learning outcomes than analogies that have been shown as text and static pictures ($d = 1.45$, a very large effect).

The study by Goldstone and Son (2005) focused on what is the best way to present simulation materials along the dimension concrete-idealized. This refers to the amount of detail and the extent to which graphical elements contain sufficient information to identify the real-world, concrete entity being represented. They conducted two experiments comparing four conditions in which the concreteness of the first of two simulations was manipulated: consistently concrete elements, consistently abstract elements, concreteness fading, and concreteness introduction. The results indicate that there was a difference across conditions between students' performance on the simulation itself and on a transfer test. Although performance on the simulation itself was best supported by concrete elements, idealized graphics appeared to be more effective in supporting transfer to an abstractly related simulation. The authors recommend combining both concrete and idealized formats, a conclusion that is consistent with theories that predict more general schemas when the schemas are multiply instantiated (e.g., Gick & Holyoak, 1980, 1983). The most effective sequence appears to be to start with concrete representations and let these become more idealized over time.

3.2.2. Varying degrees of immersion

The reviewed computer simulations discussed above were presented to the students on a computer screen. To investigate the influence of immersion, special attention was paid by the researchers in the following studies to the effects of presenting simulations by alternative media.

Using a 3D virtual environment called "Virtual Water", Trindade, Fiolhais, and Almeida (2002) compared viewing a simulation on screen with viewing it by using stereoscopic glasses. They also investigated the influence of students' spatial ability on conceptual understanding of the contents of the simulation. Their study reveals that 3D virtual environments can support achievement of a better conceptual understanding of some content –especially content that allows for more interactivity– by students with high spatial abilities. However, stereoscopic visualizations did not seem to contribute much to conceptual understanding, even though the stereoscopic view did indeed provide some sense of immersion.

In a study by Moreno and Mayer (2004) students learned to design the roots, stem and leaves of a plant so that it could survive in five different virtual reality environments. Two interventions were developed based on two different methodological approaches: based on an instructional media approach, the game was presented via desktop computer (low immersion) or head-mounted display (high immersion); based on an instructional approach, students were spoken to in a personalized (e.g., including *I* and *you*) or nonpersonalized (e.g., third-person monologue) manner. Results indicate that students learn more deeply when they are spoken to in a conversational style ($d_{\text{retention}} = 0.94$ and $d_{\text{problem solving}} = 1.79$, a very large effect) rather than a formal style. However, the cutting-edge educational technology did not lead to better performance on tests of retention and transfer, even though students reported higher levels of physical presence with high rather than low immersion. The authors therefore recommend using high-immersion virtual reality only when the immersion is the focal point of instruction, and not to add it as a way to induce physical presence for its own sake.

In the present literature review, the study by Mitnik et al. (2009) is the only one where the group of students working with the computer simulation served as the control group. This study focused on the effect of an educational activity with robots for improving the ability to produce and interpret line graphs. Students had to graph different linear movements performed by a mobile robot. The experimental group worked on the activity in a face-to-face computer-supported collaborative learning situation, with wirelessly interconnected handhelds and robots. Results indicate that the robots activity appeared to be nearly twice as effective ($d = 1.14$, a very large effect) as the computer simulation activity in improving students' ability to interpret line graphs. The robot activity was considered more motivating and fostered collaboration among students. According to the authors the motivation of the students in the experimental group was –contrary to the control group– not based on novelty, but on immersion in the activity, which stimulated students' commitment and involvement throughout the entire experiment.

Another example of the abandonment of the computer screen as simulation medium is SMALLab: a semi-immersive mixed-reality learning environment that integrates computer-generated data with real-world components. In investigating the potential impact of SMALLab use on student-driven collaborative learning in the domain of earth science, Birchfield and Megowan-Romanowicz (2009) found that mixed-reality technology can cause both student discussion exchanges and learning outcomes to increase.

3.2.3. Summary and discussion

The increasing quality of visualizations –boosted by ongoing ICT-developments– does not necessarily translate into better learning. Although some effects of visualization were found, with a maximum effect size of 1.14, most studies showed no effect. Regarding the comparison of different types of representation, the research shows that concrete representations provide the best support within a simulation itself, and idealized graphics most effectively support transfer to an abstractly related simulation (Goldstone & Son, 2005). Not only is it recommended to combine different types of representation, it is also essential to combine representations with supportive measures, as insufficient support can hamper effectiveness (Ploetzner et al., 2009). It should be kept in mind that these recommendations may depend on the domain under consideration and the exact tasks the participants are given.

Some researchers took the comparison between different representations a step further. Instead of using the computer screen as the only medium of presentation, they used different kinds of technology, allowing for investigation of the influence of *immersion*. Providing this sense of immersion by using a stereoscopic view contributes little (Trindade et al., 2002) or not at all (Moreno & Mayer, 2004) to test performance. Moreno and Mayer found that the style in which students are addressed is a more important factor of influence on learning. Achieving conceptual understanding within 3D virtual environments does appear to be facilitated by higher spatial abilities (Trindade et al., 2002). Using robots seems to be an effective way not only to immerse students in an educational activity, but also to increase learning

results, as it improves students' ability to interpret line graphs (Mitnik et al., 2009). Mixed-reality technology has the potential to support student discussion interchanges and learning outcomes (Birchfield & Megowan-Romanowicz, 2009).

Overall, it seems that improvements of learning outcomes by fostering a sense of immersion are better supported by mixing technology with reality (i.e., by using robots or SMALLab), in comparison to immersing students in virtual reality (i.e., by using a head-mounted display or stereoscopic glasses).

3.3. Comparison between different kinds of instructional support

In their review of discovery learning in simulation environments, de Jong and van Joolingen (1998) recommend the analysis of learning problems and the evaluation of ways to support learning as principal items for the research agenda. In the present review *instructional support* clearly emerges as the most investigated theme, as the presence of 19 studies in this section reveals. We begin by reviewing studies that explicitly relate their theoretical background to Scientific Discovery Learning, and subsequently discuss studies that are based on other theories. Table 3 provides specific details on the studies reviewed in this section.

3.3.1. Supporting Scientific Discovery Learning

By combining four different scaffolding components (*structural, reflective, subject-matter* and *enrichment*) in four different configurations (ranging from low to full support), Fund (2007) investigated the influence of these support programs on students' knowledge and understanding. In particular, the structural component that supplied a general framework for solving problems yielded significant differences, having a consistent and potent impact on learning outcomes. However, a combination of structural and reflective components was necessary for improved learning outcomes. Both reflective and subject-matter components had cumulative benefits over time. The reflective component appeared to stimulate meta-cognitive processes, which could have been generated because the obligation to write down solutions led to an internal dialog. A study by Zhang, Chen, Sun, and Reid (2004) also compared different kinds of supportive measures for inquiry learning. They propose a three-fold approach for supporting scientific discovery learning: it should take place in a *meaningful, systematic* and *reflective* manner.

By reviewing computer simulations from the vantage of research on perception and spatial learning, Lindgren and Schwartz (2009) introduced four learning effects to clarify aspects of simulation design: *picture superiority, noticing, structuring, and tuning*. The authors conclude that simulations facilitate improved learning and adaptation for students upon entry into the non-simulation environment. However, they warn that attempting to make the resemblance between the simulation and non-simulation environments as high as possible might undermine the simulation's pedagogical properties, such as well-chosen images, contrasting cases, and the recognition of structure.

In a review of research, Blake and Scanlon (2007) introduce a set of features for the effective use of simulations for science teaching in the context of distance learning. They conclude that to be scientifically useful, simulations should be based on realistic events and data. Other useful features are the use of multiple representations and graphs as well as the possibility of watching graphs develop in real-time during the experiment. The authors recommend that all simulations should be provided with means for customizing the activities to the students' ability levels, and that a narrative should be provided for the students to follow, either within the simulation itself or by the use of accompanying notes.

Veermans et al. (2006) compared the effects of scaffolding via implicit and explicit heuristics (see Fig. 3). In an implicit-heuristics learning environment, the heuristics were used in offering support but without offering the heuristics themselves, while in an explicit-heuristics learning environment the heuristics themselves were also made explicit to the students. Results indicate that students in both conditions improved in their domain knowledge. Process analyses suggest that offering explicit heuristics facilitates more self-regulation in students.

To examine the effects of integrating and/or linking multiple dynamic representations on learning outcomes, van der Meij and de Jong (2006) experimented with three different conditions in a learning environment on the physical subject of moments: separated, non-linked representations (S-NL), separated, dynamically linked representations (S-DL), and integrated, dynamically linked representations (I-DL). The best results were generally seen for participants in the condition in which the representations were integrated and dynamically linked. Participants in that condition also experienced the learning environment as easiest to work with. Overall, participants learned from working with the learning environment. However, simply linking representations dynamically did not lead to improved learning results in comparison with non-linking. The authors believe that the requirement to mentally translate between different representations is a good way to acquire deeper knowledge in a domain.

By assigning students to one of three inquiry learning tasks in an unknown domain, Lazonder, Wilhelm, and van Lieburg (2009) investigated whether it is sufficient for students merely to have knowledge about the variables in the simulation, or whether having a basic understanding about how these variables are interrelated is also necessary. The *concrete* task contained known variables, from which hypotheses about their relations could be deduced. The *intermediate* task used known variables, but the deduction of their interrelatedness was not possible. The *abstract* task contained unknown variables for which hypotheses about their relations could not be deduced. Results show that the concrete participants performed more successfully ($d_{\text{concrete vs. intermediate}} = 0.82$) and efficiently, whereas no difference could be detected between the intermediate and abstract participants' achievement. The authors conclude that a basic understanding of the interrelatedness between variables is necessary for supporting the processes and outcomes of inquiry learning.

Manlove et al. (2006) researched the possibilities of offering online support for regulating collaborative inquiry learning. Students worked in small groups with a computer simulation to conduct scientific inquiry within the physical subject of fluid dynamics. Both the control group and the experimental group could use a planning support tool. The tool for the experimental group contained additional regulatory guidelines, including a hierarchy of goals and subgoals, hints and explanations, and a template for the final report. The fully specified tool appeared to provide better support for both their learning outcomes ($d = 0.98$) and their initial planning ($d = 3.5$, a very large effect). Although offering regulatory guidelines during collaborative scientific discovery learning leads to improved planning activities, the results for monitoring activities are less conclusive. In a more recent study by Manlove, Lazonder, and de Jong (2009) that also focused on regulatory software scaffolds during scientific inquiry learning, the researchers were especially interested in whether there is a difference

Table 3

Comparison between different kinds of instructional support.

Primary author (year of publication)	Science discipline	Cognitive topic	N	Interventions	Results/conclusions	Effect size (Cohen's <i>d</i>)
Supporting Scientific Discovery Learning Fund (2007)	General science	Various science problems	473	Support programs: with structure component vs. without structure component Support programs: structure component with reflective component vs. structure component without reflective component	More effective work patterns, better knowledge construction and understanding More constructivist knowledge acquisition and deeper understanding	* *
Lazonder et al (2009)		Meaning of and relations between variables	57	Concrete task vs. intermediate task Intermediate task vs. abstract task	More successful performance Equally successful performance	0.82 n.a.
Zhang et al (2004)	Physics	Floating and sinking	Study 1: 80 Study 2: 30	Experimental support AND interpretative support AND reflective support vs. no support	Better (meaningful, systematic, and reflective) discovery learning	*
Veermans et al (2006)		Collisions	30	Heuristics: implicit with explicit vs. implicit without explicit	More self-regulation	*
van der Meij and de Jong (2006)		Moments	72	Representations: integrated, dynamically linked vs. separate, non-linked	Low complexity part: no difference in learning results on domain knowledge High complexity part: better learning results on domain knowledge	n.a. *
				Representations: separate, dynamically linked vs. separate, non-linked	No difference in learning outcomes	n.a.
				Representations: integrated, dynamically linked vs. separate, dynamically linked OR separate, non-linked	Easiest working experience	0.99 (I,DL vs. S,DL) 0.96 (I,DL vs. S,NL)
Manlove et al (2006)		Fluid dynamics	17	Support tool with regulatory guidelines vs. support tool without regulatory guidelines	Better learning outcomes Better initial planning	0.98 3.50
Manlove et al (2009)			30	Collaborative use of regulative software scaffolds vs. individual use of regulative software scaffolds	Higher learning outcomes and no difference in frequency and duration of regulative scaffold use	0.23 (report structure) 0.83 (report content) 1.16 (model quality)
Saab et al (2007)		Collisions	38 pairs	RIDE collaboration instruction vs. control	More and effective discovery learning activities and more constructive communication, but no difference in discovery learning results	n.a.
Instructional support approached from other perspectives						
Ketelhut and Nelson, (2010)	Biology	Epidemiology	500	Experimentation: virtual vs. physical	No difference in engagement or learning outcomes	n.a.
Ketelhut et al (2010)			± 2000	Curriculum variations: expert modeling and coaching OR legitimate peripheral participation vs. guided social constructivist OR control	Multiple-choice test: better understanding of scientific inquiry	*
				Curriculum variations: guided social constructivist vs. expert modeling and coaching OR legitimate peripheral participation OR control	Written letter test: better understanding of scientific inquiry	*
Gonzalez-Cruz et al (2003)	Chemistry	Enzyme kinetics	119	Guidance: intermediate instructions vs. detailed instructions OR minimal instructions OR additional class session OR control	Short term: better preparation of reports	*
				Guidance: intermediate instructions vs. minimal instructions	Long term: no difference in performance	*
Lee (2007)		Boyle's Law and Charles' Law	257	Visual treatment: spatial contiguity AND visual-cue scaffolding vs. control	High spatial ability: no difference in performance on comprehension and transfer tests Low spatial ability: better performance on comprehension and transfer tests	n.a. 0.32 (comprehension) 0.17 (transfer)
Papastergiou (2009)	Computer science	Computer memory	88	Gaming vs. non-gaming	More effective in promoting conceptual knowledge More motivational (enjoyment, engagement and interest)	0.64 0.76

Barab et al (2009)	General science	Water quality	51	Immersive world dyad OR immersive world single-user vs. expository textbook dyad	Better performance on proximal items	1.39** (IW,D vs. ET,D)
				Immersive world dyad vs. expository textbook dyad	Better performance on distal items	1.25** (IW,S vs. ET,D)
				Immersive world dyad vs. simplistic framing dyad OR expository textbook dyad	Better performance on open-ended transfer task	1.09** (IW,Dvs.SF,D)
Bell and Trundle (2008) Trundle and Bell (2010)	Physics	Moon phases	50	Computer simulation (pretest–posttest)	Better scientific understanding	1.60** (IW,D vs. ET,D)
			157	Observations: computer simulation vs. computer simulation AND from nature vs. from nature	No difference in gain of knowledge about lunar shapes or the ability to explain the cause of moon phases	*
				Observations: computer simulation AND from nature vs. computer simulation OR from nature	No difference in gain of knowledge about lunar sequences	n.a.
				Observations: computer simulation vs. from nature	Higher gain of knowledge about lunar sequences	n.a.
				Computer simulation (pretest–posttest)	Better scientific understanding	*
Gazit et al (2005)		Astronomical phenomena	10	Computer simulation (pretest–posttest)	Better scientific understanding	*
Clark and Jorde (2004)	Thermodynamics		120	Visualization with an integrated tactile model vs. visualization without an integrated tactile model	Better explanations	0.94
					Better predictions	0.51
Kester et al (2004)	Electrical circuits		88	Timing of information: supportive before AND procedural during practice vs. supportive before AND procedural before practice	Fewer information searching behaviors	1.18
				Timing of information: supportive before AND procedural during practice vs. supportive during AND procedural before practice	Fewer information searching behaviors	1.35

Note. The reviews by Bell, Urhahne, Schanze, and Ploetzner (2010), Blake and Scanlon (2007) and Lindgren and Schwartz (2009) are not included. All studies are presented in order of discussion in this review, grouped by science discipline. Calculation of Cohen's *d*: n.a. = not applicable; * = not possible, based on the methods by Thalheimer and Cook (2002); ** = equal group sizes assumed.

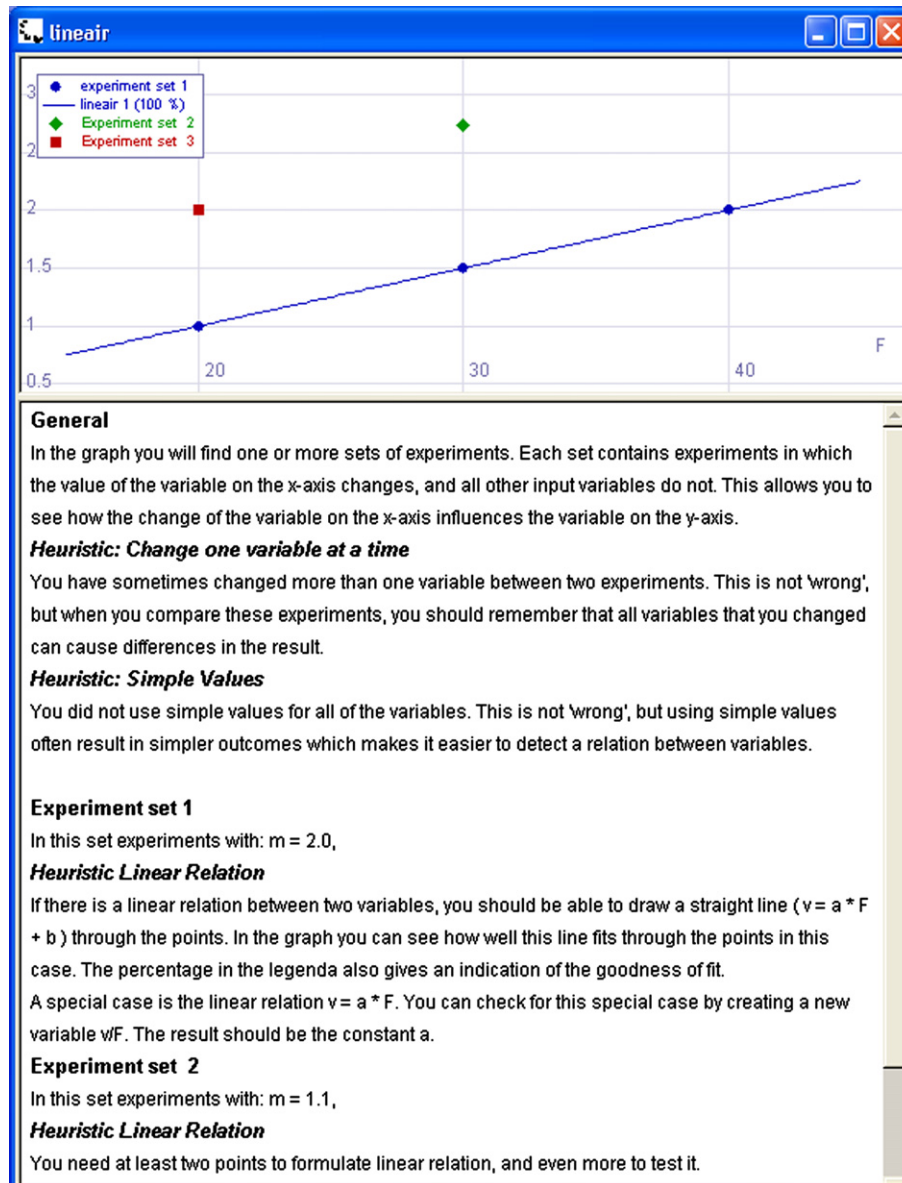


Fig. 3. Scientific Discovery Learning supported by heuristics that are both implicit and explicit, studied by Veermans et al. (2006). Printed with permission.

between paired and single students as far as the use of regulative scaffolds is concerned. The results show that the pairs scored significantly better than individual students on learning outcomes ($d_{\text{report structure}} = 0.23$, $d_{\text{report content}} = 0.83$ and $d_{\text{model quality}} = 1.16$, a very large effect). Contrary to the researchers' expectations, collaboration did not seem to have any effect on the use of regulatory scaffolds, which remained fairly low for both pairs and singles. According to the authors, this might be related to a persistent problem: the availability of an instrument implies neither that students will make use of it nor that their use of the instrument is effective.

Saab et al. (2007) investigated the effects for collaborative discovery learning of instructions that were based on the RIDE-rules, which are derived from four principles that they deduced from literature on collaborative processes: *Respect*, *Intelligent collaboration*, *Deciding together* and *Encouraging*. Analyses show that the RIDE-instruction can lead to more constructive communication and improved discovery learning activities. However, direct effects on scientific discovery learning outcomes were not found.

3.3.2. Instructional support approached from other perspectives

In an attempt to investigate how much guidance should be offered to students working on a computer simulation on the subject of enzyme kinetics, Gonzalez-Cruz, Rodriguez-Sotres, and Rodriguez-Penagos (2003) compared groups that were supported with three different levels of instructions (detailed, intermediate or minimal) with a group that solved problems in class and a group without additional support sessions. Results show that students using the instruction support program significantly benefited compared to students that did not make use of it. In the short term, the intermediate instructions were more convenient in helping the students to prepare reports, while in the long term both the intermediate and minimal instructions performed equally well. The authors state that offering students some freedom while they use the computer simulation is more beneficial, as long as the tutor still reviews and comments on their work afterward. The strategy they therefore recommend is the intermediate level of instruction, where both freedom and structure are offered.

Mayer's spatial contiguity principle was the basis for Lee's (2007) investigation of the effects of a visual treatment on students' understanding and transfer of chemistry knowledge. The principle was applied with regard to the distance of images on the screen and by adding visual-cue scaffolding to the simulation. The number of icons and the distance between interrelated icons were varied in the experimental condition, and a monitoring tool was added. The extent to which the visual treatments interacted with students' spatial ability was also investigated. The visual treatment led to achievement of significantly higher results on comprehension and transfer tests ($d_{\text{comprehension}} = 0.32$ and $d_{\text{transfer}} = 0.17$; both small effect sizes). An interaction effect was also found: students with low spatial abilities performed better in the treatment group compared to the control group, whereas students with high spatial abilities achieved equal results regardless of condition.

The effectiveness of using a computer simulation in promoting scientific understandings was researched by Bell and Trundle (2008), who integrated the planetarium software program "Starry Night Backyard" with instruction on moon phases. The computer simulation served as a reliable way to consistently collect data, instead of playing a dominant role in the foreground as an instructional feature. Therefore the authors consider the results of this study as support for the assumption that educational technologies should facilitate established effective instructional materials, instead of replacing them. A follow-up study (Trundle & Bell, 2010) shows that learning about moon shapes and the ability to explain the cause of moon phases can be supported equally by this simulation, observations from nature, or a combination of both. However, learning by using only the computer simulation resulted in higher gain of knowledge about lunar sequences, compared to learning based on observations from nature alone. Gazit, Yair, and Chen (2005) also performed research on the development of students' conceptual understanding of astronomical phenomena, focusing on real-time learning processes of students using a "Virtual Solar System". Even though they conclude that their simulation can support the development of scientific understanding, they stress that students' high interactive performance might not be sufficient for conceptual development to take place should sufficient orientation and navigation tools be lacking.

By comparing two groups of students that used a computer simulation in the course "Probing your Surroundings", Clark and Jorde (2004) investigated the extent to which the revision of students' ideas about thermal equilibrium could be facilitated by the integration of a tangible model in a visualization. While trying to figure out why objects feel the way they do, students in the augmented visualization condition could use a tangible model, in addition to the thermal equilibrium visualization that was available to the control group as well. This tangible model consisted of a different representation of the problem and a picture of a hand with an arrow next to it that –when an object was clicked– showed the heat flow to and from the hand depending on the temperature gradient between the hand and the object. Students in the experimental group appeared to be better able to understand thermal equilibrium, by demonstrating a better ability to explain why objects feel the way they do ($d = 0.94$), as well as by being better able to predict the temperature of objects in different surroundings ($d = 0.51$).

In an attempt to find the optimal timing for offering different kinds of information to students using a computer-based simulation, Kester, Kirschner, and van Merriënboer (2004) compared four information presentation formats. These formats varied two factors: the timing of offering supportive information (before or during task practice) and the timing of offering procedural information (before or during task practice). Students' information searching behavior revealed that they most needed supportive information before the task and procedural information during task practice. The authors argue that it is possible to determine optimal moments of presentation for these different kinds of information based on the specific task requirements during simulations.

The next two studies approach the provision of support by introducing a gaming element. Even though we included these studies in our review as they meet our inclusion criteria for computer simulations, we recognize these studies' focus blends into the subject of gaming, being a distinct research area.

The aim of a study by Papastergiou (2009) was to determine the learning effect and motivational appeal of an educational game about learning computer memory concepts. Two educational applications were compared, one with and the other without a gaming approach. The gaming approach appeared to be effective in improving students' knowledge about computer memory ($d = 0.64$), as well as more motivating ($d = 0.76$) than the non-gaming approach. Even though boys were more involved in computer games than girls as far as enjoyment, experience and domain knowledge were concerned, there was no significant difference in the extent to which boys and girls learned by using the game. Boys and girls also experienced the game as equally motivating. Based on the results of this study the author concludes that digital game-based learning can be used as an educational environment within high school education, because educational games can increase knowledge of subject-matter, as well as improve students' enjoyment, involvement and interest in the learning process.

The application of games as a curricular scaffold was also studied by Barab et al. (2009), for a 3D game-based curriculum designed to teach water quality concepts. The conditions they compared –*expository textbook dyad*, *simplistic framing dyad*, *immersive world dyad* and *immersive world single-user*– allow for relating their results to several themes that have already been covered in our review thus far. Concerning *visualization*, both immersive-world conditions performed significantly better on proximal items ($d_{\text{IW,D vs. ET,D}} = 1.39$ and $d_{\text{IW,S vs. ET,D}} = 1.25$, both very large effects) than the non-immersive *expository textbook* condition. This study can also be related to the research by Moreno and Mayer (2004), as Barab et al. (2009) compared their immersive world conditions in which information was written in the first person to a simplistic framing condition in which information was written in the third person. As already discussed in subsection 3.2.2, Moreno and Mayer (2004) found that manner of address had a significant influence on learning, with a conversational style leading to deeper learning compared to a formal style. Consistent with those findings, Barab et al. (2009) found that immersive world dyads outperformed simplistic framing dyads ($d_{\text{IW,D vs. SF,D}} = 1.09$) and expository textbook dyads ($d_{\text{IW,D vs. ET,D}} = 1.60$, a very large effect) on an open-ended transfer task. However, the simultaneous variation of immersion and narrative voice between conditions does not allow for an exact determination of narrative voice.

"River City" is another example of a 3D immersive virtual environment. This multi-user environment allows students to move around through a virtual town and perform collaborative inquiry in order to discover why the residents are getting ill. Extensive research on the learning effects of this environment shows that students' engagement and learning outcomes can be improved to an extent that is comparable to what can be achieved with physical experimentation (Ketelhut & Nelson, 2010). However, a comparison between different curriculum variations showed that the extent to which inquiry learning is supported depends on whether learning outcomes are tested by using multiple-choice questions or writing letters to the mayor of River City (Ketelhut, Nelson, Clarke, & Dede, 2010). The authors suggest that the latter method might be more appropriate for scientific inquiry assessment, as it is a more authentic activity than a multiple-choice test.

3.3.3. Summary and discussion

The above collection of research publications illustrates the kaleidoscope of possibilities for providing instructional support. The research on how to support Scientific Discovery Learning uses a variety of approaches. Zhang et al. (2004) propose three perspectives (*meaningful*, *systematic*, and *reflective*) and recommend approaching the development of learning support in simulation environments from all three perspectives. According to Fund (2007), who compared four scaffolding components (*structural*, *reflective*, *subject-matter*, and *enrichment*), the structural component has the most potent impact on learning outcomes. Nevertheless, several researchers recommend offering both structure and freedom, as restricting freedom too much can weaken learning results (Chang et al., 2008; Gonzalez-Cruz et al., 2003).

Research into the basic conditions for supporting computer simulation learning processes shows positive effects of support, with effect sizes up to 3.50. The following recommendations can be given: students' self-regulation is best facilitated by providing heuristics explicitly instead of implicitly (Veermans et al., 2006), and the best timing for providing information is before task practice as far as supportive information is concerned and during task practice for procedural information (Kester, Kirschner, & van Merriënboer, 2004). It is necessary for learners to have a basic understanding of the variables that are involved (Lazonder et al., 2009). Where different representations are used, requiring mental translation between them supports the acquisition of deeper domain knowledge (van der Meij & de Jong, 2006).

Research on learning with computer simulations in collaboration shows that relations between collaborative learning processes and individual learning outcomes are not straightforward. Even though the RIDE-instructions by Saab et al. (2007) improved discovery learning activities, the students' learning results did not improve. In comparison to working on discovery learning activities individually, collaborating in pairs can indeed significantly improve learning outcomes (Manlove et al., 2009). Providing collaborating groups of students with additional regulatory guidelines can also improve learning results (Manlove et al., 2006).

A recurrent finding in the research on instructional support is that it is of utmost importance to provide students with a learning environment in which freedom and structured support are well-balanced, which is in line with research on the ineffectiveness of minimally guided instruction (Kirschner, Sweller, & Clark, 2006). Even though the research on providing instructional support has been fruitful, and allows us to deduce useful recommendations, the majority of studies approached the provision of support only *from within* the simulation: e.g., by adding a human-teacher-like support system (Fund, 2007). This leaves the question of how optimal instructional support by teacher guidance or curricular embedment could be provided largely unanswered.

3.4. Classroom settings and lesson scenario

Most reviewed interventions up to this point zoomed in on the use of computer simulations per se. When used in an educational context, the role of computer simulations within the classroom lesson has several aspects worthy of attention. First, we focus on the influence of student engagement on learning. We subsequently discuss how learning can be supported by scripting diverging activities during the lesson scenario. Table 4 provides specific details on the studies reviewed in this section.

3.4.1. Varying levels of engagement

In a study by Wu and Huang (2007), students' behavioral, emotional and cognitive engagement were investigated by comparing classrooms having differing instructional approaches. In a student-centered class, the topic of forces and motion was introduced by the teacher and students subsequently worked with computer simulations and completed assignments in pairs. Although the scientific concepts were also introduced by the teacher in the teacher-centered class, students did not have computers at their disposal: instead the teacher used a projector linked to a laptop to demonstrate the simulations and to guide the students in completing their learning activities. The researchers found that students' prior achievement levels could interact with instructional approaches, as low-achieving students benefited more from the teacher-centered approach ($d = 1.07$). Even though the emotional engagement of the students in the student-centered classroom was greater, the level of emotional engagement did not appear to have an impact on students' achievement.

However, Laakso, Myller, and Korhonen (2009) found a result that appears to contradict this finding. They compared groups of students who worked on simulated algorithm exercises, using different levels of the "Extended Engagement Taxonomy". These levels range from presenting a visualization to other students (as being the highest level of engagement) to just viewing a visualization or no viewing at all (as being the lowest levels). Merely viewing algorithm animations appeared to be insufficient to achieve learning, even when it was possible to

Table 4
Classroom settings and lesson scenario.

Primary author (year of publication)	Science discipline	Cognitive topic	N	Interventions	Results/conclusions	Effect size (Cohen's d)
Varying levels of engagement						
Laakso et al (2009)	Computer science	Binary heap	75	Engagement levels: changing vs. viewing	Better learning performance	0.68
Wu and Huang (2007)	Physics	Force and motion	54	Classes: student-centered vs. teacher-centered	More emotional engagement, but no difference in learning achievements	n.a.
				Interaction effect: teacher-centered AND low-achieving students	More benefit from the teacher-centered approach	1.07
The roles of teacher guidance and collaboration						
Limniou et al (2009)	Chemistry	Acid-base titration	Study 1: 80 Study 2: 80	Virtual simulation vs. traditional laboratory	No difference in learning outcomes	n.a
Dori and Belcher (2005)	Physics	Electromagnetism	811	Technology Enabled Active Learning vs. traditional teaching	Better conceptual understanding and learning outcomes	*
Shieh et al (2010)		Mechanics Electromagnetism	Study 1: 113 Study 2: 386		No difference in learning gains Higher learning gains	n.a. 0.39

Note. All studies are presented in order of discussion in this review, grouped by science discipline. Calculation of Cohen's d : n.a. = not applicable; * = not possible, based on the methods by Thalheimer and Cook (2002).

share understandings and misunderstandings with a partner while watching the visualization. According to the authors, learning environments should be designed specifically to act on the higher levels of the engagement taxonomy, because such learning environments can stimulate learning activities to become more active and more student-centered.

As both of these studies on the theme of *engagement* not only used different ways to operationalize the construct, but also used different measurement procedures, speculation on what caused the conflicting results is troublesome. While Wu and Huang (2007) consider engagement to be a multifaceted construct implying behavioral, emotional, and cognitive participation in learning experiences, Laakso et al. (2009) base their engagement levels on screen captures and voice recordings of students' activities. Moreover, whereas the study by Wu and Huang (2007) contains a detailed description of teacher guidance, the study by Laakso et al. (2009) lacks specification of how the learning processes were supported by the teacher.

3.4.2. The roles of teacher guidance and collaboration

An example of actively involving teacher guidance is the attempt by Dori and Belcher (2005) to make the learning process more social by adopting a method that includes peer-collaboration and the use of a Personal Response System. They investigated the effects in the social, cognitive and affective domains of studying in small groups while working with a computer simulation in the so-called TEAL-project: an environment for Technology-Enabled Active Learning. Following mini-lectures on electromagnetism in class, the students were requested to respond to multiple-choice questions in real time, after which the students' response distribution was shown in bar graphs on a classroom screen. When there was no agreement, the teacher asked the students to try to come to an agreed-upon answer by peer-discussion in groups of three students. Repeating the same multiple-choice question to the class afterward often resulted in more consensus on the supposedly correct answer. Compared to traditional teaching, the TEAL-students significantly improved their conceptual understanding. In the small-scale experiment, the majority of participants also recommended the course to fellow students, indicating the advantages of interactivity, visualization, and hands-on experiments. The authors conclude the TEAL-environment can have a strong positive influence on students' learning results, because this technology supports active learning. Likewise, an implementation of the TEAL-environment at a university in Taiwan (Shieh, Chang, & Tang, 2010) during two semesters led to higher learning gains in the second semester ($d = 0.39$) compared to traditional teaching.

In the study by Duran et al. (2007), a description of a software-based method was given in which the simulations were not just used as demonstrations, but were included within a method that promotes students' understanding and participation (as discussed earlier in this review). After the presentation of a real-world scenario and theoretical explanations of the main concepts of a chapter, students were challenged to predict the evolution of the scenario. In the brainstorm session that followed, the students could have a discussion in groups about the scenario's evolution. In this phase, the teacher could mix with the students to clarify doubts they might have and guide discussions. At the end of their discussions the ideas of the groups were collected. Subsequently the simulation was run to check whether the predictions by the students were right or not, instead of the correct answers being presented by the teacher. Finally, after discussion and theoretical explanation, the collected ideas were contrasted with the results of the phenomena that were shown in the simulation stage.

In a study that was focused on the difference in the communication venue, Limniou, Papadopoulos, and Whitehead (2009) compared a course where the students used synchronous face-to-face communication with a course in which the teacher and students communicated in an asynchronous way by using a "WebCT environment". The teachers had different roles in these two environments: in the synchronous condition the teacher had a more active role in guiding the students in achieving learning outcomes by face-to-face discussion and interaction, whereas in the virtual environment the role of the teacher was more supportive, aimed at asking questions and the collection of resources to support independent learning. As both approaches led to the same learning outcomes, the authors assert that this gives teachers more freedom in choosing a feasible approach depending on university facilities, the staff's time and the students' familiarity with virtual learning environments.

3.4.3. Summary and discussion

As different operationalizations of the construct *engagement* were used among researchers, its influence remains unclear, although effect sizes up to 1.07 were found. Laakso, Myller, Korhonen (2009) stress that learning activities should be as active and student-centered as possible by promoting the use of learning environments that function on the higher levels of engagement. In a study by Wu and Huang (2007), however, student achievement was not affected by emotional engagement. Embedding computer simulations in a didactic environment can –besides having an impact on learning processes and outcomes– influence the role of the teacher and classroom communication. Collaboratively working on computer simulations may allow more active learning, which in turn improves students' conceptual understanding (Dori & Belcher, 2005; Shieh et al., 2010). Even when different teaching approaches lead to the same learning outcomes, the choice of a specific approach can still have an impact on the role of the teacher in terms of the need to provide guidance to the students (Limniou et al., 2009).

To gain knowledge about the optimal application of computer simulations within science education, research should be approached from both a *zoomed in* perspective –by manipulating variables within a simulation– and a *zoomed out* perspective –by taking the broader pedagogical context into account. The scarcity of studies that zoomed out, however, shows that most researchers have investigated the effectiveness of computer simulations without including such factors of influence as teacher guidance, classroom session scenarios or curricular characteristics.

4. Conclusions

We started this review with two main questions. The first of these regards the extent to which traditional science education can be enhanced by using computer simulations, and the second regards how simulations and their instructional support are best shaped and implemented to optimize the use of simulations themselves. The reviewed articles provide information from an experimental perspective. In this section we discuss the major trends and results found.

With respect to the use of simulations as enhancement or replacement of traditional means of testing the results are unequivocal: simulations have gained a place in the classroom as robust additions to the repertoire of teachers, either as an addition to available

traditional teaching methods or as a replacement of parts of the curriculum. All reviewed studies that compare conditions with or without simulations report positive results for the simulation condition for studies in which simulations were used to replace or enhance traditional lectures. Effect sizes up to 1.5 for posttest scores and above 2 on scores related to motivation and attitude were found for this situation. The replacement of laboratory activities by simulations or their use as preparatory laboratory activities is a special case of this. Here a large gain in efficiency of learning can be reported. Very large effect sizes for time on task are reported with simulation-based instruction on the favored side. Another effective way of using simulations is as a preparatory activity for real laboratory activities. Positive effects are found for the comprehension of the lab task as well as for practical laboratory skills during the real lab activity.

The latter finding brings us to an important issue. The acquisition of laboratory skills is often a learning goal in itself which cannot be completely replaced by simulations. However, it becomes clear that, as in domains where simulation has already been widely accepted as a training facility –such as flight simulation– simulations can play an important role in making lab activities more effective by offering the simulation as a pre-lab training.

The second research question has two parts: in what ways were simulations enhanced to try to improve their success and what were the effects of these enhancements? In the studies that we reviewed two main themes were investigated: the way the simulation results are presented visually as well as instructional support provided to the learner during work on the simulation.

With respect to visualization, most studies reviewed considered the representation of simulation output data. No unequivocal results were reported in the studies reviewed, partly because the number of studies that could be found was relatively small and because they vary in the kind of representation that they investigated. There is one outstanding result: the visualization of invisible phenomena that was investigated by [Trey and Khan \(2008\)](#). A large learning effect on these unobservable phenomena was found, which is in line with one of the main advantages of computer simulation hypothesized by de Jong and colleagues ([van Berkum & de Jong, 1991](#); [van Joolingen & de Jong, 1991](#)). With respect to the level of immersion in 3D simulations, no study found a big effect for immersion as such. Effects were found for additional instruction as well as for the use of robots for learning on the use of graphs ([Mitnik et al., 2009](#)). The fact that immersion as such does not clearly contribute to learning effects has a probable cause in the lack of a clear function of the immersion. Embodiment of abstract concepts could provide such a function ([Tall, 2008](#)) and deserves attention in future research.

At the level of instructional support, a large variety of supportive measures has been studied in the research reviewed. About half of these studies concern the use of scientific discovery learning and the processes needed. A review by [Alfieri, Brooks, Aldrich, and Tenenbaum \(2011\)](#) showed the necessity of providing learners in a discovery environment –although not necessarily with simulations– with instructional support. The types of support can still be classified along the lines identified by [de Jong and van Joolingen \(1998\)](#): support for transitive learning processes –for instance, hypothesis generation and the design of experiments– as well as regulative processes aiming at the planning and monitoring of learning activities. The eight studies in this category report positive results on a variety of variables. Few report effect sizes or enough data to compute an effect size, but the overall impression is that effects are moderate. It is also noteworthy that most of these studies report effects on the learning process and direct outcomes of these processes, indicating that strong results on posttests could not be achieved. This does not disqualify these studies, but points to the long-standing problem associated with discovery learning that discovery methods by their nature take some time to have an effect, as dual learning goals are being pursued: learning of domain knowledge as well as learning of discovery skills.

The other instructional interventions that are not aimed at discovery learning show positive effects, but it is impossible to deduce general trends from these, as the domain and the kinds of intervention vary. Here it becomes clear that the space of options for intervention, as well as the space for the design of the simulations themselves is very large, making it difficult to extract general trends. The fact that quite large effect sizes can be obtained by varying the design and instructional support shows the importance of careful use of simulations and instructional design. General guidelines are of only limited value here, making the design of simulation-based instruction an engineering science. The reviewed studies show that effects of well-designed simulation-based instruction are potentially high. The main factors that need to be considered are the way the learner is addressed and involved, the way information from the simulation is presented and integrated, what additional information is presented, and how this presentation is timed.

The effects of computer simulations in science education are caused by interplay between the simulation, the nature of the content, the student and the teacher. A point of interest for the research agenda in this area, as mentioned by [de Jong and van Joolingen \(1998\)](#) in their review, is to investigate the place of computer simulations in the curriculum. Most of the studies we reviewed however, investigated the effects of computer simulations on learning *ceteris paribus*, consequently ignoring the influence of the teacher, the curriculum, and other such pedagogical factors. In order for educational innovations such as computer simulations to be successful, teachers need to be provided with the necessary skills and knowledge to implement them ([Pelgrum, 2001](#)). Without proper teacher skills, the full potential of simulations, such as their suitability for practicing inquiry skills, may remain out of reach. Instead, they may be used as demonstration experiments or be completely controlled by the teacher ([Lindgren & Schwartz, 2009](#)). Reducing the use of computer simulations to a step-by-step cookbook approach undermines their potential to afford students with an opportunity to freely create, test and evaluate their own hypotheses in a more richly contextualized environment ([Windschitl & Andre, 1998](#)).

Whereas the outcomes of the studies reviewed by [de Jong and van Joolingen \(1998\)](#) were not univocally in favor of simulations, the majority of studies we reviewed suggest an improvement in effectiveness over the past decade. We believe this has mainly been caused by an ongoing synergy of technological advancements and improvements of instructional support. Although (quasi)experimental research of recent years has certainly been fruitful, we recommend that the focus on different kinds of visualizations and supportive measures be extended to a more comprehensive view, for example by including the lesson scenario and the computer simulation's place within the curriculum as factors of influence. Additionally embedding the role of the teacher would be a promising step forward in the establishment of a pedagogical framework for the application of computer simulations in science education.

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