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Thinking Outside the Box: Enhancing Science Teaching by Combining (Instead of Contrasting) Laboratory and Simulation Activities

by

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Abstract

The focus of the present work was on 10- to 12-year-old elementary school students' conceptual learning outcomes in science in two specific inquiry-learning environments, laboratory and simulation. The main aim was to examine if it would be more beneficial to combine than contrast simulation and laboratory activities in science teaching. It was argued that the status quo where laboratories and simulations are seen as alternative or competing methods in science teaching is hardly an optimal solution to promote students' learning and understanding in various science domains. It was hypothesized that it would make more sense and be more productive to combine laboratories and simulations. Several explanations and examples were provided to back up the hypothesis.

In order to test whether learning with the combination of laboratory and simulation activities can result in better conceptual understanding in science than learning with laboratory or simulation activities alone, two experiments were conducted in the domain of electricity. In these experiments students constructed and studied electrical circuits in three different learning environments: laboratory (real circuits), simulation (virtual circuits), and simulation-laboratory combination (real and virtual circuits were used simultaneously). In order to measure and compare how these environments affected students' conceptual understanding of circuits, a subject knowledge assessment questionnaire was administered before and after the experimentation. The results of the experiments were presented in four empirical studies. Three of the studies focused on learning outcomes between the conditions and one on learning processes.

Study I analyzed learning outcomes from experiment I. The aim of the study was to investigate if it would be more beneficial to combine simulation and laboratory activities than to use them separately in teaching the concepts of simple electricity. Matched-trios were created based on the pre-test results of 66 elementary school students and divided randomly into a laboratory (real circuits), simulation (virtual circuits) and simulation-laboratory combination (real and virtual circuits simultaneously) conditions. In each condition students had 90 minutes to construct and study various circuits. The results showed that studying electrical circuits in the simulation–laboratory combination environment improved students' conceptual understanding more than studying circuits in simulation and laboratory environments alone. Although there were no statistical differences between simulation and laboratory environments, the learning effect was more pronounced in the simulation condition where the students made clear progress during the intervention, whereas in the laboratory condition students' conceptual understanding remained at an elementary level after the intervention.

Study II analyzed learning outcomes from experiment II. The aim of the study was to investigate if and how learning outcomes in simulation and simulation-laboratory combination environments are mediated by implicit (only procedural guidance) and explicit (more structure and guidance for the discovery process) instruction in the context of simple DC circuits. Matched-quartets were created based on the pre-test results of 50 elementary school students and divided randomly into a simulation implicit (SI), simulation explicit (SE), combination implicit (CI) and combination explicit (CE) conditions. The results showed that when the students were working with the simulation alone, they were able to gain significantly greater amount of subject knowledge when they received metacognitive support (explicit instruction; SE) for the discovery process than when they received only procedural guidance (implicit instruction: SI). However, this additional scaffolding was not enough to reach the level of the students in the combination environment (CI and CE). A surprising finding in Study II was that instructional support had a different effect in the combination environment than in the simulation environment. In the combination environment explicit instruction (CE) did not seem to elicit much additional gain for students' understanding of electric circuits compared to implicit instruction (CI). Instead, explicit instruction slowed down the inquiry process substantially in the combination environment.

Study III analyzed from video data learning processes of those 50 students that participated in experiment II (cf. Study II above). The focus was on three specific learning processes: cognitive conflicts, self-explanations, and analogical encodings. The aim of the study was to find out possible explanations for the success of the combination condition in Experiments I and II. The video data provided clear evidence about the benefits of studying with the real and virtual circuits simultaneously (the combination conditions). Mostly the representations complemented each other, that is, one representation helped students to interpret and understand the outcomes they received from the other representation. However, there were also instances in which analogical encoding took place, that is, situations in which the slightly discrepant results between the representations 'forced' students to focus on those features that could be generalised across the two representations. No statistical differences were found in the amount of experienced cognitive conflicts and self-explanations between simulation and combination conditions, though in self-explanations there was a nascent trend in favour of the combination. There was also a clear tendency suggesting that explicit guidance increased the amount of self-explanations. Overall, the amount of cognitive conflicts and self-explanations was very low.

The aim of the *Study IV* was twofold: the main aim was to provide an aggregated overview of the learning outcomes of experiments I and II; the secondary aim was to explore the relationship between the learning environments and students' prior domain knowledge (low and high) in the experiments. Aggregated results of experiments I & II showed that on average, 91% of the students in the combination environment scored above the average of the laboratory environment, and 76% of them scored also above the average of the simulation environment. Seventy percent of the students in the simulation environment scored above the average of the laboratory environment. The results further showed that overall students seemed to benefit from combining simulations and laboratories regardless of their level of prior knowledge, that is, students with either low or high prior knowledge who studied circuits in the combination environment outperformed their counterparts who studied in the laboratory or simulation environment alone. The effect seemed to be slightly bigger among the students with low prior knowledge. However, more detailed inspection of the results showed that there were considerable differences between the experiments regarding how students with low and high prior knowledge benefitted from the combination: in Experiment I, especially students with low prior knowledge benefitted from the combination as compared to those students that used only the simulation, whereas in Experiment II, only students with high prior knowledge seemed to benefit from the combination relative to the simulation group. Regarding the differences between simulation and laboratory groups, the benefits of using a simulation seemed to be slightly higher among students with high prior knowledge.

The results of the four empirical studies support the hypothesis concerning the benefits of using simulation along with laboratory activities to promote students' conceptual understanding of electricity. It can be concluded that when teaching students about electricity, the students can gain better understanding when they have an opportunity to use the simulation and the real circuits in parallel than if they have only the real circuits or only a computer simulation available, even when the use of the simulation is supported with the explicit instruction. The outcomes of the empirical studies can be considered as the first unambiguous evidence on the (additional) benefits of combining laboratory and simulation activities in science education as compared to learning with laboratories and simulations alone.

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I still remember the day back in 1997 when I, as a second year masters student, first entered the basement of Educational Technology Unit in Lemminkäisenkatu carrying a broken floppy disk in my hands. That day awakened my interest in computers, which later expanded to an enthusiasm for conducting research in the field of educational technology.

Research is sometimes lonely work that requires a great deal of perseverance and discipline. Fortunately, it is also a joint effort, so this is the moment to thank all those who contributed to this work one way or the other.

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In Kaarina, May 2012

Tomi Jaakkola

List of original publications

This doctoral thesis is based on the following four empirical studies reported in four original articles. The studies are referred to in the text by their roman numerals:

I Jaakkola, T. & Nurmi, S. (2008). Fostering Elementary School Students' Understanding of Simple Electricity by Combining Simulation and Laboratory Activities. *Journal of Computer Assisted Learning,* 24(4), 271-283.

II Jaakkola, T., Nurmi, S. & Veermans, K. (2011). A comparison of students' conceptual understanding of electric circuits in simulation only and simulation-laboratory contexts. *Journal of Research in Science Teaching*, 48(1), 71-93.

III Jaakkola, T., Nurmi, S., & Lehtinen, E. (2010). Conceptual change in learning electricity: using virtual and concrete external representations simultaneously. In L. Verschaffel, E. De Corte, T. de Jong, & J. Elen (Eds.) *Use of representations in reasoning and problem solving. Analysis and improvement. New Perspectives in Learning and Instruction Series* (pp. 133-152). NY: Routledge.

IV Jaakkola, T. & Nurmi, S. (2008). Instructional Effectiveness of Learning Objects. In L. Lockyer, S. Bennett, S. Agostinho & B. Harper (eds.) *Handbook of Research on Learning Design and Learning Objects: Issues, Applications and Technologies* (pp. 532-552). New York: Information Science Reference.

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1. Introduction

Research on learning shows that students learn better when they have an active role in the learning process and their understanding of scientific principles is formulated within the framework of their prior knowledge (Bransford, Brown & Cocking, 2000; Simon, 2000). In inquiry learning students are engaged in active exploration process; the answers are not directly visible to them; instead, they are guided to conduct their own experiments in the subject matter and gradually induce (de Jong, 2006) or deduce (Chen, 2010) the answers and underlying principles from these investigations. While conducting the experiments, the students are also able to test their own conceptions and compare these with the results of the experiments (de Jong, 2006; Lehtinen & Rui, 1996; Wieman, Adams & Perkins., 2008). Traditional instruction is typically teacher-centred, and the emphasis is on learning of factual knowledge (Bransford et al., 2000). Consequently, students are often in a more passive role and have fewer opportunities to put their own conceptions under testing relative to inquiry learning. These apparent differences can explain why experiments show rather unanimously that inquiry learning—given that the inquiry process is properly guided (de Jong, 2006; Mayer, 2004)—results in better conceptual understanding than traditional instruction (Baki, Kosa & Guven, 2009; Finkelstein et al., 2005; Minner, Levy & Century, 2010; Taylor & Chi, 2006; Zacharia & Olympiou, 2011).

This thesis focuses on the learning of conceptual knowledge in science in two specific inquiry-learning environments, laboratory and simulation. In laboratory learning environments (hereafter laboratory), students conduct hands-on experiments with *real* equipment and materials. In simulation learning environments (hereafter simulation), they use computer-based simulation software to conduct hands-on experiments with *virtual* equipment and materials.

Laboratories have a long history and a distinctive role in science education (see Hofstein & Lunetta, 2004, for a review). Proponents of laboratories have typically emphasised that authentic experiences with real materials are essential for learning (e.g. NSTA, 2007). Consequently, their argument against the use of simulations has been that computers deprive students of hands-on manipulation of real materials and distort reality (e.g. Armstrong & Casement, 1998). Despite the criticism, simulations have become an increasingly popular alternative to laboratories because they are safe, portable, highly customizable (e.g. Frederiksen, White & Gutwil, 1999), and potentially less expensive (Klahr et al., 2007) than laboratories. Furthermore, empirical evidence shows that learning with simulations typically results in equal (Klahr et al., 2007; Triona & Klahr, 2003; Yuan, Lee & Wang, 2010; Zacharia & Constantinou, 2008) or sometimes even better (Finkelstein et al., 2005; Chang, Chen, Lin & Sung, 2008) conceptual learning outcomes than learning in laboratory. In this light, it is no surprise that many researchers suggest that the use of simulations should be increased in science education (e.g. Finkelstein et al., 2005; Zacharia & Constatinou, 2008). The most radical proposition has been that simulations should replace laboratories (e.g. Klahr, Triona & Williams, 2007; Triona & Klahr, 2003).

The above shows how laboratories and simulations are typically considered as competing and mutually exclusive methods in science teaching and learning. The laboratory proponents' reluctant attitude toward the use of simulations, for instance, entails that simulations have nothing good to offer for learners of science compared to laboratories. Equally, the notion that simulations should replace laboratories assumes that because simulations produce at the minimum equal learning outcomes compared to laboratories, the benefits that simulations can provide to learners overlap the benefits of laboratories.

The main aim of this thesis is to investigate the unique strengths and weaknesses of laboratories and simulations in science education and whether it would be more beneficial to combine than contrast these two representations in order to promote students' conceptual understanding. My argument is that the above kind of juxtaposition—"to simulate or not to simulate" (Steinberg, 2000, p.37)—between laboratories and simulations is hardly an optimal solution in inquiry-based science teaching context. My hypothesis in this thesis is that, for three major reasons, it would make more sense and be more productive to combine laboratories and simulations. The first reason to combine laboratories and simulations is that different learners can benefit from different representations. Research on learning shows that individual learning environments produce considerable variance in learning performance among learners, indicating that there is not a single learning environment or representation that would be 'ideal' or 'optimal' for all students. Multiple representations ensure a better 'match' between learner and representation than a single representation. The second reason to combine laboratories and simulations is that laboratories and simulations complement each other. Each representation has specific features (strengths) that can help students to discover and understand certain aspects of the domain more effectively than the other representation. Each representation has also specific features (weaknesses) that can complicate learning of domain knowledge. By using the representations simultaneously, the weaknesses of one representation can be compensated and patched by the strengths of the other. The third reason to combine laboratories and simulations is that multiple representations allow learners to view the domain from different perspectives and compare (the output of) the representations. Research on analogical learning shows that making comparisons between multiple representations or cases that overlap—in the present case laboratories and simulations—can activate deeper processing of the content and better understanding of the domain than use of only a single representation (laboratory or simulation alone). The rationale for combining laboratories and simulations will be presented in more detail later.

In order to test whether learning with the combination of laboratory and simulation activities can result in better conceptual understanding in science than learning with laboratory or simulation activities alone, two experiments were conducted. In these experiments learning outcomes and processes of the students who were involved in the combined simulation and laboratory activities were contrasted with the outcomes and processes of those who were involved only in the simulation activities or only in the laboratory activities. The results of the experiments are presented in four empirical studies that are included in the thesis.

Hitherto, there have been only a few attempts (Campbell, Bourne, Mosterman & Brodersen, 2002; Ronen & Eliahu, 2000; Zacharia, 2007; Zacharia, Olympiou & Papaevripidou, 2008) to explore the potential benefits of combining and linking laboratory and simulation activities in science education. Unfortunately, various shortages in these studies make it impossible to evaluate the true effectiveness of the combination. The studies included in the thesis were designed to overcome these limitations.

The present doctoral dissertation consists of a theoretical and methodological summary and the four original, empirical studies. In the summary section, first, a theoretical framework for combining rather than contrasting laboratory and simulation activities is presented. Second, the methodological solutions of this work are described. Third, the set of studies is overviewed with regard to the overall and specific aims of the doctoral dissertation. Fourth, a critical examination of the theoretical and methodological basis of this work is conducted, and fifth, the challenges for future studies on this domain are presented.

1.1. Unique strengths and weaknesses of laboratories and simulations

The following sections in this chapter are dedicated to reviewing and discussing the specific features (strengths) in laboratories and in simulations that can contribute positively to students' understanding of scientific phenomena and their learning of scientific knowledge, and, in contrast, the features (weaknesses) in each representation that can hinder its effectiveness and interfere in learning.

1.1.1. Strengths of laboratories

Laboratories offer a fruitful environment for learning of scientific knowledge because the learning takes place in an authentic context. In laboratory, students obtain relevant sensory experiences from working with real apparatus and materials, and they acquire procedural skills and knowledge about conducting real science; this cannot typically be achieved with simulations (Chen, 2010). According to Flick (1993; 2007) procedural knowledge and skills that students learn in laboratory can contribute directly to the development of conceptual knowledge because the physical contact with real equipment triggers unique brain activities.

In laboratory the testing (and re-testing) can take considerably longer than in simulation because setting up and disassembling real equipment typically takes more time than with virtual equipment. This holds especially for the disassembling part, because in simulation everything can be reset by a mouse click (Campbell et al., 2002; Klahr et al., 2007; Triona & Klahr, 2003). While it is true that the fast manipulation in simulation opens up possibilities to conduct more experiments, at the same time, there is a danger that the 'speediness and easiness' will result in a random and unproductive experimentation. In this sense the 'slowness' of laboratory can be perceived as an advantage because it may encourage careful planning and more thorough thinking prior to acting (experimenting) because the errors are more costly.

Authentic learning context that laboratories provide may be especially helpful when students are inexperienced. Winn and his colleagues (2006), for instance, compared the effectiveness of real experience and a computer simulation to promote students' learning in oceanography. They found no differences in overall learning outcomes between the two environments, but a more detailed analysis revealed that the real experience helped contextualize learning for students with little prior experience of the ocean. Laboratories can also be productive when students have already gained some prior experiences. Learning in laboratories takes place in a context that is very similar (or sometimes even identical) to the context where students' intuitive conceptions originate. This means that learning can be easily linked to students' personal experiences. It is well established that in order to promote conceptual learning in science, it is not enough to provide students with accurate information. It is equally important to activate their prior conceptions, because misconceptions that are an integral part of initial conceptions can prevent learning and (especially) application of accurate information (e.g., Chi, 2008; Vosniadou, 2002). As Wiser and Amin (2001) have shown, a good strategy to promote conceptual learning is to use the scientific view to explain everyday experiences and thus point out the limitations in students' initial reasoning and validate the better applicability of the scientific explanation.

1.1.2. Weaknesses of laboratories

Despite the aforementioned benefits, learning of conceptual knowledge can be challenging in laboratory. According to physics Nobel laureate Carl E. Wieman and his colleagues (2008), one of the main challenges in laboratories is that students are faced with too many details and too much complexity from the beginning. As novices, students lack the knowledge and skills needed to filter relevant information. For instance, it has been observed than students pay needless attention to trivial aspects in laboratories, such as colour of wires in electrical circuits (Finkelstein et al., 2005). Furthermore, measurement errors and other anomalies, which are an inseparable part of conducting real science and thus considered as an important part of scientific literacy (Chen, 2010), create noisy data that makes it challenging for students to make generalisations and discover underlying principles. Hennessy, Deaney, and Ruthven (2006) have also argued that the development of a theoretical understanding of complex phenomena through practical manipulation can be problematic because in many cases students can see what is happening only on the surface level, while being unable to observe and grasp the underlying processes and mechanisms that are invisible in natural systems and often important for theoretical understanding (e.g. current flow).

1.1.3. Strengths of simulations

Educational simulations are designed to mimic reality. A distinctive feature and the strength of simulations is that the embedded models are ideal rather than completely accurate replicas of reality (hence the word model). In other words, simulations represent a version of reality that is simplified to a certain extent by design. Chen (2010), for instance, who reviewed more than 200 educational simulations, reports that approximately 80% of the simulations provided a simplified model of reality and virtually all (99%) excluded any source of error or anomaly. Exclusion of elements that are 'irrelevant' (e.g. color of wires in electrical circuits, cf. Finkelstein et al., 2005) or that can otherwise interfere with learning of conceptual knowledge (e.g. conductivity and resistance of wires in circuits; friction and air resistance in motion), for instance, allows students to focus on elements that are the most important for theoretical understanding (e.g. relationship between battery voltage and bulb voltage in various circuit configurations or how an external force will affect the speed and direction of the motion of an object). Absence of anomalies and measurement errors helps students to discover underlying theoretical principles, because it means that the simulation will produce consistent output and consequently the students can observe a perfect match between the data and the theory. Frederiksen et al. (1999), for instance, have demonstrated in the domain of electricity that using 'intermediate' or 'transitional' models in a simulation environment prior to exposing the scientific model in its full complexity can be an extremely effective means to promote students' understanding of scientific phenomena. Although the circuit laws and mechanisms are invariably represented and communicated through algebraic equations and formulas within the scientific community, extensive research shows that these principles can't be taught effectively to students directly as equations because they lack an appropriate qualitative knowledge base needed to interpret and apply the quantitative information properly (Hart, 2008; McDermott & Shaffer, 1992; Plötzner, 1995). In order to overcome this pedagogical challenge, Frederiksen and his colleagues asked students to first investigate two intermediate qualitative models of electrical circuits in a simulation environment, prior to exposing the algebraic model of electrical circuits. Pre-test–post-test comparison revealed that the intervention resulted in a large developmental effect in students' conceptual understanding of electrical circuits. It should be noted that intermediate models can be implemented only in the virtual world; in the real world it is possible to explore only with factual models.

Simulations can also simplify reality on a perceptual level, that is, the physical fidelity of a simulation—or the perceptual concreteness of the elements within a simulation—may vary in a continuum from highly concrete, detailed, and realistic representations to simplified and formalised abstract illustrations. The physical fidelity of a simulation can greatly affect what the students learn from the simulation and how they can utilize that knowledge. A simulation with perceptually concrete elements is easier to understand, but at the same time, an extensive amount of detail can make it more difficult for students to generalize the findings and apply them beyond the original context (Ainsworth, 2006; Goldstone & Son, 2005). The objective of a simulation with a more abstract form is to highlight the generalizability of the representations and findings at the expense of realistic and contextual details; the cost here is that the simulation becomes more difficult to understand (see Goldstone & Son, 2005, for a detailed review on benefits and drawbacks of using concrete and abstract elements in a simulation).

Besides simplification, simulations can also provide unique details that aid students in better understanding and learning about the domain under investigation. Finkelstein et al. (2005), for instance, describe a study in which they examined the effects of substituting a computer-simulation for real circuits to learn the basics of DC circuits in a university physics course. Contrary to real circuits, the simulation enabled students to observe continuously the electron flow inside the circuits[1]. The outcome was that the students using the simulation outperformed the students using the real circuits both on a conceptual knowledge test and in the coordinated tasks of assembling real circuits and explaining how they worked. The authors explain that the fact that the simulation provided direct perceptual access to the concept of current flow helped students to gain better understanding of the functioning of DC circuits. To further highlight the effect of this specific benefit to 'show the invisible', Zacharia and Constantinou (2008), in the domain of heat and temperature, and Klahr et al. (2007), in the domain of kinetics, did not find differences in learning outcomes between students using real equipment and those using a simulation. The discrepancies in results between the studies can be explained by the fact that in Zacharia and Constantinou as well as in Klahr et al. studies the elements in laboratory and simulation environments were identical, whereas in the Finkelstein et al. study the unique visualisations embedded into the simulation environment enabled the students to get better insight into the domain.

[1] The existence of current cannot be observed in real circuits (you can, of course, measure it). A computer-based simulation can easily show whether or not there is a flow inside a circuit, the path of that flow, and possibly even its magnitude. Such lack of adequate information plays a role in many misconceptions about electric circuits (e.g., a bulb will still light up when only one wire is attached; or, as a bulb consumes current, there is no/less current after the bulb than before) (e.g., McDermott & Shaffer, 1992; Reiner et al., 2000) and makes it more difficult to learn the scientific model.

1.1.4. Some unclear and conditional strengths of simulations

Some of the benefits simulations can provide are less clear than others. One frequently used argument in favour of simulations is their efficiency; simulations allow faster experimentation and manipulation of materials compared to laboratory. Klahr et al. (2007), for instance, report a study where students assembled and tested either 'real' or virtual mousetrap cars in order to discover an optimal configuration for the maximum distance the car could travel. The main outcome was that students learned equally well in both environments, but it took approximately three times less time to assemble and test a virtual mousetrap car than a 'real' mousetrap car, thus indicating higher efficiency[2] of the simulation environment. However, a closer look at the study leads to rather different interpretation; the design included two independent constraints for the experimentation, meaning that the students had either a fixed number of cars they could construct or a fixed amount of time in which to construct them. These results reveal that learning with simulation was efficient only in cases in which the number of cars was constrained; these students spent three times *less* time on the experimentation than in any other condition, but they learned equally well. In the case when the time was constrained the use of the simulation became considerable less effective, or even unproductive; these students assembled and tested three times *more* cars than students in any other condition, but they did not learn more. Thus, it can be concluded that although the faster manipulation in the simulation environment allowed the students to carry more experiments compared to laboratory, this additional effort did not result in additional gain in knowledge. In other words, there is no evidence that the speed of experimentation or the amount of conducted experiments would be directly linked to learning outcomes.

Some of the benefits that simulations can offer for learners are conditional. This means that before a specific benefit can be utilised, certain perquisites need to be met. In the worst scenario, unless a perquisite(s) is met, a conditional benefit might turn out to be harmful rather than helpful. In Marshall and Young's (2006) study, for instance, a student trio used first a pair of real pucks and later a pair of virtual pucks to explore collision. Learning from the virtual pucks offered possibilities for generating more sophisticated theory than real pucks, because with the latter the students had to rely merely on qualitative observation (what they could see) whereas the simulation included more variables that could be manipulated and offered more detailed feedback (e.g. 'hidden' vectors). However, the outcome was that the richness of the simulation resulted in additional processing time and less effective and sophisticated theory development than laboratory. One explanation for the outcome is that the students were provided with only a modest guidance on how to use the simulation and they received no scaffolding for how to react to the system feedback and how to interpret and integrate data from various output. In other words, the lack of training and scaffolding might have prevented the group from benefiting from the enriched feedback (cf. de Jong, 2006; Mayer, 2004). The Marshall and Young study also illustrates that it is not given that the use of a simulation will automatically result in faster experimentation compared to laboratory; due to the problems with interpreting and inte-

[2] Rasch & Schnotz (2009) define learning efficiency as learning outcome per learning time. When analyzing learning outcomes, the underlying question is whether certain instructional conditions will stimulate more elaborate cognitive processing and, therefore, result in better learning outcomes. When analyzing learning efficiency, we ask how well the effort (time) and the processing stimulated by each instructional condition translates to learning outcomes.

grating the system feedback, the group used twice as much time in the simulation environment than in the laboratory.

1.1.5. Weaknesses of simulations

Despite some obvious benefits, such as simplification of reality and provision of additional details, learning with simulations can also create unique problems and challenges. One of the main challenges and questions in teaching and learning with simulations is how effectively simulations succeed in activating students' prior conception, and how well the students are able to use and apply the knowledge they learn in a simulation environment. As we know from past literature, it is very difficult, or even impossible, to promote conceptual change effectively without properly activating students' prior conceptions (Chi, 2008; Vosniadou, 2002; Wiser & Amin, 2001). Activation of students' prior conceptions can be particularly challenging in a simulation environment because the learning takes place in a virtual space, whereas the origins of the student's prior conceptions are typically derived from everyday experiences that take place in real context. In other words, there is a danger that the students are unable to map and relate the learning experiences in a simulation environment with their own previous experiences. To give an example, Tao and Gunstone (1999) were able to alter students' conceptions of mechanics to some extent during the intervention by using a set of simulations, but a delayed post-test revealed that most of the students had regressed to their initial conception. Thus, one explanation of why the intervention was only moderately effective could be that the (virtual) instruction was unable to fully activate students' prior conceptions.

Learning with simulations can create problems even when students are able to relate the simulations to their prior experiences. While idealised models embedded to simulations can make it easier for students to discover the basic principles of a domain and help them to learn relevant knowledge, the cost of simplification is that it will create a certain amount of gap or mismatch between theory and reality—the more the model simplifies, the greater the gap between theory and reality. Consequently, in case the students are not made aware of the limitations of the model embedded to a simulation as a representation of reality, this can lead to confusion if the output or feedback of the simulation is in conflict with the intuitive physics students have inferred from real-world experiences (e.g. friction and air resistance are not modelled as part of acceleration and deceleration). Such conflicting situations can make students question the authenticity of simulations; students may think, for instance, that there is a bug in a simulation (Ronen & Eliahu, 2000), or they may not consider simulations as 'real' or 'serious' learning environments (Hennessy & O'Shea, 1993; Srinivasan et al., 2006). From this angle, another explanation for the kind of problem that Tao and Gunstone reported could be that after learning with the simulation, the students doubted the simulation and were thus unwilling to trade in their initial conceptions for those revealed in simulation.

1.2. Rationale for combining laboratories and simulations

The following sections in this chapter provide a rationale for combining laboratory and simulation activities in science education. The latter part of the chapter presents different ways to combine laboratory and simulation activities and discusses the premises and potential consequences of each combination.

1.2.1. Different learners, different representations

The first motive to combine laboratories and simulations is that different learners can benefit from different representations and availability of two representations increases the likelihood that students can learn with the representation that best matches their needs as compared to the situation when only a single representation is available. The fact that laboratories and simulations are typically considered as competing learning environments in science education indicates that advocates of each representation assume that there is an 'ideal' way to present and explore a domain, and that every student interprets the features of a learning environment in an 'ideal' or 'optimal' way. In reality, however, learning in a particular environment produces a considerable amount of variance in learning processes and outcomes between students. Kennedy and Judd (2007), for instance, analysed log files to investigate the relationship between intended and observed user behaviours in a computer-based simulation environment in the domain of medicine. Their analysis revealed that only about a quarter of students used the simulation as the developers had intended. Chang and colleagues (Chang et al., 2008) who found that learning about the basic characteristics of an optical lens was significantly enhanced in simulation as compared to laboratory, report that the students with higher abstract reasoning capabilities especially benefited from the use of simulation. Winn and his colleagues' (2006) found no differences in overall learning outcomes between simulation and laboratory environments, but their more fine-grained analyses revealed that the real experience was especially helpful and important for inexperienced students, because it helped contextualize learning, whereas the simulation made it easier for students (that apparently had some prior experiences) to connect what they learned from it to other content they learned in class. Veermans, de Jong and van Joolingen (2006) also found no differences in students' average learning outcomes between two simulation environments; however in their case factors mediating learning appeared to be very different between environments. These examples show that learning environments in general, and laboratories and simulations in particular, are not always interchangeable as they have affordances toward different learners.

1.2.2. Unique and complementary strengths

The second motive to combine laboratories and simulations is that laboratories and simulations complement each other. In previous chapter we learned about specific features (strengths) of each representation that can help students to discover and understand certain aspects of the domain more effectively than the other representation. It was argued, for instance, that in laboratories students can learn unique procedural knowledge and skills that may also contribute (uniquely) to the development of conceptual knowledge. Furthermore, while conducting experiments in laboratory, students have to deal with various anomalies and nuances that help them to learn about differences between models and reality (Chen, 2010). Equally, simulations can highlight processes and concepts that are (the most) important for theoretical understanding and they can provide unique details that aid students in better understanding and learning about the domain under investigation. It was also shown in previous chapter that besides the strengths, each representation has also specific features (weaknesses) that can complicate learning of domain knowledge. By using the representations simultaneously, the weaknesses of one representation can be compensated and patched by the strengths of the other. For instance, a simulation that simplifies reality and produces consistent output can help students to interpret and make sense of the results more easily than the noisy output in laboratory. Likewise, inclusion of laboratories can make it easier for students to link the new information with their prior experiences.

1.2.3. Comparison promotes deeper and more generalised understanding

The third motive to combine laboratories and simulations is that multiple representations allow learners to view the domain from different perspectives (cf. Simon & Larkin, 1987) and compare (the output of) the representations. Research on analogical learning shows that making comparisons between multiple representations or cases that overlap—in the present case laboratories and simulations—can activate deeper processing of the content and better understanding of the domain than use of only a single representation (laboratory or simulation alone) (Gick & Holoyak, 1983; Kalyuga, Chandler, & Sweller, 1998; Kolloffel, Eysink, de Jong & Wilhelm, 2009; Thompson, Gentner & Loewenstein, 2000). With a single representation, learners are easily drawn toward irrelevant surface features, which often result in overgeneralizations and understanding that is highly contextualised and superficial (Ainsworth, 2008; Gentner & Medina, 1998). In the Finkelstein et al. (2005) study (described in the previous chapter), for instance, students who used real equipment to construct electric circuits were frequently in doubt about the effects that the colour of a wire could have on a circuit behaviour. With two overlapping representations (such as laboratories and simulations) of the domain, learners can compare and relate the structure of the representations, which allows them to both identify the shared invariant features of the representations and the features that are unique to each individual representation (Ainsworth, 2008; Gentner, Loewenstein & Thompson, 2003). This makes it easier to learn relevant domain knowledge, because those features that are shared across both representations also illustrate/highlight the central structures and principles of the target domain. Related to the examples used in the previous section this could mean that the simplified simulation not only helps students to interpret and make sense of the results more easily, but it can also help them to understand the noisy output of laboratory. Likewise, inclusion of laboratories would help students to understand what the simulation represents and to realize that the findings they have observed in a simulation also have correspondence to phenomena in reality (Campbell et al., 2002; Ronen & Eliahu, 2000).

1.2.4. Empirical evidence

There are only a few empirical studies, most of them conducted in the domain of electricity, that have investigated the relative effectiveness of combining laboratories and simulations in science education as compared to using the two representations alone. Ronen and Eliahu (2000) report a study in which all students (age 15 years) solved circuit assignments using real circuits. In the experimental group the students had also an opportunity to use a simulation to build and sketch circuits (in control group they could sketch only on paper), but they were not explicitly instructed to use the simulation, as the computer monitor was turned off. The outcome was that those students who decided to use the simulation were more efficient in drawing corresponding schematics and more accurate (fewer errors) at constructing requested real circuits than students who didn't use the simulation. Campbell et al. (2002) investigated learning of electricity among beginning electrical engineering students. In the laboratory condition the students used only real equipment, whereas in the combination condition they conducted first all the experiments virtually using a simulation, and then in the end, repeated two of the virtual experiments with real equipment. The outcome was that the students in the combination condition outperformed the students in the laboratory condition in a written lab and theory knowledge post-test. More recently, Zacharia has reported an identical result in the domains of electricity (Zacharia, 2007) and heat and temperature (Zacharia, Olympiou, & Papaevridipou, 2008). In these studies the laboratory group was using real equipment throughout the intervention, whereas the combination group switched from real equipment to simulation in the latter part of the intervention.

Though the above results could mean that combining laboratories and simulations can provide additional benefits for learning of scientific knowledge as compared to learning with laboratories and simulations alone, the incomplete designs of the studies leave plenty of room for alternative explanations. Because none of the studies included 'pure' simulation conditions as a control for the combination condition, it is impossible to judge whether it was the combination of laboratory and simulation activities, or merely the simulation that caused the positive learning effect relative to laboratory. Furthermore, because of this defect, these studies cannot provide any information concerning the effectiveness of the combination relative to a simulation alone.

The effectiveness of learning with multiple representations and from multiple cases has been studied more extensively in the context of some more traditional representational formats. Gick and Holoyak (1983), for instance, asked students to solve a radiation problem. Prior to introducing the problem, the students in the control condition were asked to read an analogical story that included a solution that also applied to the radiation problem. In the experimental condition the students read two analogical stories that both introduced the same solution principle. The outcome was that those students who read the two analogs were significantly more likely to apply the correct solution principle to the radiation problem as compared to those who studied only one analog. The authors explain that reading the two analogical stories helped students to discover, extract, and apply the correct solution because the principle was embedded in both stories. In the domain of combinatorics and probability, Kolloffel and his colleagues (2009) compared the effects of learning from diagrams, equations, and text alone to the effects of learning from the combination of text and equations as well as diagrams and equations. The information content was equivalent in all representations. The combination of text and equations yielded the best learning outcomes, whereas the other combination condition, diagrams and equations, did not stand out from any of the three single representation conditions. Kalyuga, Chandler, and Sweller (1998) report longitudinal data in which a group of trainees studied electrical circuits either from a diagram alone or from the diagram and an explanatory text that was designed to help interpret the diagram. In the beginning the trainees clearly benefited from the text that was embedded to the diagram, but as their level of expertise grew, they learned better from the diagram alone.

Thus, it can be concluded that learning with multiple representations or from multiple cases can, and often does, result in better learning outcomes than learning from a single representation or case. However, as the level of students' expertise grows, the benefits of learning with two overlapping representations might lose some of its effects, and at certain point, the second representation might even become unnecessary. On the other hand, this applies only if the representations are completely overlapping. Larkin and Simon (1987), for instance, have demonstrated that even experts use and benefit from multiple representations because each representation can provide unique angles to the problem or the domain. In other words, if the representations are genuinely complementary, as is the case with laboratories and simulations in many domains (cf. previous chapter), then one would expect that learning with multiple representations will always be more effective than learning with a single representation (Ainsworth, 2008).

1.2.5. Sequential or parallel combination?

There are principally two different ways to combine laboratories and simulations (or mix of any other representations). In a *sequential combination*, laboratories and simulations are always used at different phases of the experimentation. In Zacharia's studies (Zacharia, 2007; Zacharia et al., 2008), for instance, which consisted of three parts, the students in the combination condition used only real equipment in the first two parts of the intervention and only simulation in the last part. In a *parallel combination,* each experiment is conducted back-to-back with both representations. In Ronen & Eliahu's (2000) study, for instance, students first constructed a real circuit, and then immediately after, they (re-)constructed an identical virtual circuit using a simulation. Thus, the main difference between sequential and parallel combinations is that laboratories and simulations are *never co-present* in the former, whereas they are *always co-present* in the latter.

The decision whether to choose sequential or parallel combination can have considerable impact on students' performance, as we will shortly learn. Interestingly, the studies that have combined laboratories and simulations have predominantly chosen sequential combination—of the above-cited four studies (Campbell et al., 2002; Ronen & Eliahu, 2000; Zacharia, 2007; Zacharia et al., 2008), only Ronen and Eliahu used a parallel combination, whereas those studies that have combined other representational formats have exclusively used the parallel combination (Gick & Holoyak, 1983; Kalyuga et al., 1998; Kolloffel et al., 2009).

Both sequential and parallel combinations have pros and cons. On one hand, the sequential combination may pose less cognitive load on students at the baseline, because they have to deal and monitor only one representation at a time. In the parallel combination students have to manage and coordinate between two representations. Tabachneck-Schijf and Simon (1998), for instance, have demonstrated that students may sometimes experience considerable difficulties in coordinating between and integrating information from two representations that are simultaneously available.

On the other hand, in the parallel combination, laboratories and simulations act simultaneously as sources of information that can help students to understand the domain under investigation— whatever is understood in one representation can be used to interpret and understand the domain (e.g. Ainsworth, 2006), and if something is missed on one representation, it can still be discovered in the other. This also ensures that students have their preferred representation always available (cf. Tabachnek-Schijf & Simon, 1998). Furthermore, assuming that the coordination between the representations will be productive and perhaps even necessary for proper understanding, then parallel combination will have clear advantages. The reason is that simultaneously available representations make the comparison and the mapping process between the representations easier and less demanding on learners' cognitive resources than studying the representations in isolation (Gentner et al., 2003; Thompson et al., 2000). When the representations are used sequentially, in isolation, students' understanding relies on a single representation at the time, and the mapping of information between the representations will be heavily dependent on memory retrieval (Ainsworth, 2006; Kurtz, Miao & Gentner, 2001), which is cognitively sensitive and computationally demanding process (Gick & Holoyak, 1980).

Research conducted in the framework of analogical learning, or more specifically analogical encoding, offers strong evidence for the effectiveness of parallel combination as compared to sequential combination at various levels of students' experience and expertise. Thompson, et al. (2000; also Loewenstein, Thompson & Gentner, 2003), for instance, asked experienced MBA students in two different conditions to analyse two overlapping negotiation cases that both entailed an optimal strategy for resolving a negotiation task. The outcome was that the students who analysed the cases simultaneously (parallel combination) were three times more likely to use the optimal negotiation strategies in a following real negotiation task than those who analysed the same cases in isolation (sequential combination). The authors were able to replicate this finding among undergraduate students with no prior negotiation experiences (Gentner et al., 2003). Gentner, Loewenstein, and Hung (2007) have also shown that learning with multiple representations facilitates understanding even among preschool children. The findings of the two latter studies are particularly important as they suggest that even novice learners can benefit from two overlapping representations, and that studying two cases simultaneously can be enlightening even when neither of the cases is well understood. The prototype models of analogical learning assumed that learning from analogical cases would suit only for relatively advanced and experienced learners. One of the main prerequisites in these models was that one of the cases needed to be well understood, because the well-understood case—which novice learners seldom have available—was used as an anchor and as a source of information to help students interpret and discover the properties of a corresponding, but less familiar, or more complex situation, the target (e.g. Gentner & Gentner, 1983; Gentner & Holoyak, 1997).

1.2.6. Lab or sim first?

The decision to use laboratory prior to a simulation, or vice versa, may affect the inquiry process and hence the outcomes of the inquiry in both sequential and parallel combinations. However, because of the lack of empirical evidence, it is unclear which order should be preferred.

The decision concerning the order of representations is presumably far more critical and sensitive in the sequential combination, because in this approach the representations are used in isolation. Ideally, this entails that each representation should be used whenever the benefits it can offer for learners is higher than the benefits offered by the other representation. However, in practice it is not an easy task to determine which one of the two representations can offer the highest benefits in a particular context or at a particular moment, because the true benefit is determined by both the informational and computational properties of the representation[3]. For instance, in certain situations a representation may be chosen because of its informational superiority. However, a mismatch between students' skill level and the format of the instructional representation might interfere and cancel out the informational benefits of the representation and thus even turn the relative

[3] According to Larkin and Simon (1987), informational effectiveness of a representation is determined by how much information it contains, whereas computational effectiveness of a representation is determined by how easily relevant information can be extracted and applied from it.

strengths of the representations around. To further highlight the sensitiveness of choosing between laboratories and simulation in the context of sequential combination, one commonly used rationale for starting a sequence with a laboratory work is that laboratories can help students to contextualize learning more easily than simulations, especially if the students are novices (Winn et al., 2006; Zacharia, 2007; Zacharia et al., 2008). However, it turns out that this order is not always preferable, nor that the rationale behind the order is completely accurate. To demonstrate, Smith, Gnesdilow and Puntambekar (2010) compared 6th graders learning about pulleys in a study where students either started an experimentation sequence with a laboratory and then switched to a simulation, or started with a simulation and then switched to a laboratory. The main outcome was that the students who started the sequence with the laboratory outperformed those who started with the simulation, thus supporting the common rationale for using laboratory first when students are relatively inexperienced. However, the study had one considerable limitation: the comparison between the conditions was unfair, as the groups were different already at the baseline. The group that used the laboratory first had scored significantly better in the pretest than the students who used the simulation first, meaning that the results cannot be attributed solely to the condition, as the level of prior knowledge likely affected the outcome as well. However, this limitation itself—the potential interaction between students' prior knowledge and representation format—makes these results particularly interesting. The authors administered the same subject knowledge test before, in the middle (at the point of switch of the representations), and after the intervention. The group that started off with the laboratory gained knowledge during both laboratory and simulation sessions, suggesting that both representations contributed to their understanding about pulleys. In contrary, the group that started off with the simulation gained a significant amount of knowledge during the simulation phase (though their outcomes remained behind the other condition, the slopes of the two conditions were similar, that is, the amount of knowledge that was gained during the first phase was about the same regardless whether the students had used the laboratory or the simulation), but after they had switched to the laboratory and completed all the experiments, the group actually showed lower levels of domain knowledge than before the switch. Thus, the group with lower levels of prior knowledge learned relatively well in the simulation environment, but did extremely poorly after switching to the laboratory. One straightforward explanation for this surprising regression, which would also concur with both the original conclusion and the preference to use laboratories prior to simulations, is that the simulation decontextualised learning, and consequently the students were simply unable to transfer what they had learned from the simulation to the laboratory. However, one particular issue that fights against this conclusion is the fact that the students learned from the simulation, meaning that they were able to extract and transfer successfully what they had learned in the simulation to the domain knowledge test situation. There is no reason to doubt the construct validity of the domain knowledge tests, because the group that started with the laboratory showed significant progress at the midpoint as well. Consequently, an alternative explanation for the regression would be that the students who started with the simulation couldn't handle the complexity of the laboratory, because their level of domain knowledge was simply too low. Instead, they were able to handle better the simulation environment, because the simulated model excluded friction and measurement error. This interpretation, which is in line with Wiemann et al. (2008), suggests that in some situations it may actually be easier and more beneficial for novice students to learn with simulation than with laboratory, and thus start the combination sequence with the simulation.

Which representation should one choose in cases in which students already have some prior experience? We know from previous research that in order to bring about conceptual change, it is important that the instruction activate students' prior conceptions. Consequently, in order to activate students' prior conceptions, it would be important to know before the experimentation to which representation their prior experiences are bound, and then start off experimenting with that particular representation, because a mismatch between student's prior experiences and the representational format of the instruction might suppress potential learning effects and outcomes. The more experienced and informed the students are, the less important the order of the representations is likely to be.

Another critical issue that needs to be addressed when designing a sequential combination is at what stage of the experimentation the switch from one representation to the other should be made. This could actually be one the key factors between successful and unsuccessful implementation of a sequential combination. The timing of a switch(es) will not be easy, as the decision needs to involve the assessment of the benefits of each representation from multiple perspectives (among others, content, learners' experience, and learning objectives). For instance, assuming that the alternative interpretation concerning the results of Smith et al. (2010) is true, one could argue that the switch from simulation to laboratory was made too early in the simulation-first condition, as it seems that the students were unprepared to handle the complexity of the laboratories.

As far as the order of representations is concerned, the parallel combination is a safer choice as compared to the sequential combination. The reason is that in parallel combination the representations are co-present. Consequently, instructors don't need to worry about when to use a particular representation or when to switch from one representation to the other. For instance, the contextualisation of learning is of less concern as the students will always have their preferred representation available, and there will be a (relatively good) match between the representational format of the instruction and students' skill level and prior experiences. However, the order of representations could also have some effect in the parallel combination. Parallel combination is, in a way, also sequential in nature, because each experiment is conducted back-to-back—not simultaneously—with both representations. In certain situations, for instance when students are inexperienced, it would make sense to conduct the virtual experiment first, because a simulation that simplifies reality offers fewer distractions and makes it potentially easier for students to learn relevant domain knowledge. As the virtual experiment would be replicated immediately with the real equipment, the information from the simulation can be contextualised more easily. Furthermore, this order could also help students to conduct and interpret the outcomes of laboratory experiments, as the simulation would serve as a baseline and as a point of reference. However, when a simulation precedes laboratory, it introduces one challenge in the sequential combination. In the domain of electricity, for instance, real batteries are almost never fresh (e.g. a 1.5 volt battery rarely measures 1.5 volts when measured with a voltmeter), whereas the 'idealised' virtual battery typically remains fully charged (i.e. the charge remains constant). Consequently, in case the simulation is used before the laboratory, there will be some differences between the voltmeter readings of real and virtual circuits (the amount is also dependent on how accurately the simulation is designed to model reality, e.g. do the virtual wires have resistance or not), and this discrepancy can make it more difficult for students to build cognitive links between the two representations. On the other hand, the discrepancies can also be considered as an opportunity for deeper understanding, because in order to resolve the differences, the students may have to first discover the rules governing each representation based on the data (e.g., voltmeter readings) and then infer a further abstraction from these rules that would apply to both representations (e.g., the potential difference across each branch is equal to the battery voltage). Nevertheless, this potential challenge can be avoided by using the laboratory first, because then the simulation can be adjusted to match laboratory more accurately. For instance, the voltage of the virtual battery can be adjusted to match the actual reading of the real battery.

2. Aims

The present work provides an examination of 10 to 12-year-old students' conceptual learning of simple electricity in three specific inquiry-learning environments: laboratory, simulation, and laboratory-simulation combination.

The main aim is to investigate whether, why and under which condition(s) learning in a simulation-laboratory combination learning environment can result in better conceptual learning outcomes as compared to learning in a laboratory or a simulation learning environments alone. Each of the four individual studies conducted has a specific sub-aim that contributes to the main aim:

1. The aim of the Study I, which provides a baseline for the present work, is to compare the relative effectiveness of laboratory, simulation, and simulation-laboratory combination learning environments by investigating how each environment contributes to students' conceptual development in understanding simple electricity.

2. The aim of the Study II is to explore whether and how learning outcomes in simulation and simulation-laboratory combination environments are mediated by implicit (only procedural guidance) and explicit (more structure and guidance for the discovery process) instruction.

3. The aim of the Study III is to seek theoretical explanations for the benefits of linking and combining laboratory and simulation activities by examining and comparing three specific learning processes—cognitive conflicts, self-explanations, and analogical encodings—in simulation and simulation-laboratory combination learning environments.

4. The aim of the Study IV is twofold: The main aim is to provide an aggregated overview of the learning outcomes of Studies I and II; the second aim is to explore the relationship between the learning environments and students' prior knowledge, that is, whether laboratory, simulation, and laboratory-simulation environments have a specific learning impact among students with low and high prior knowledge.

3. Methods

3.1. Participants and domain

The total sample consisted of 117 fourth, fifth, and sixth grade students (10 to 12 years old; 67 girls and 50 boys) from seven classrooms of two average urban Finnish elementary schools. More details concerning the distribution of students participating in individual experiments is shown in sections 3.3.1 and 3.3.2. Participation in the empirical studies was voluntary for all students and classrooms. Parental permission was asked for all students.

The domain of the studies was electricity, more specifically, simple electric circuits. The participants had not had any previous formal education in electricity. As this study was the student's first formal introduction to the subject of electricity, the learning goal was to establish an understanding of the relationships between the observable variables, that is, the number of bulbs, the circuit configuration, and the variations in bulb brightness. The students should learn that for a bulb to be part of a complete (or closed) circuit, its two terminals must be connected to different terminals of the battery (need for a closed circuit); current circulates around the circuit in a given direction; and the brightness of a bulb in a circuit depends not only on the number of other bulbs in a circuit, but also on the configuration of the circuit. The students were also asked to measure the bulb voltage under the assumption that observing the voltages (or potential difference) across the bulbs in different configurations could help them to better understand the variations in bulb brightness.

There were several reasons to choose the domain of electricity. 1) Electricity and electrical circuits are part of elementary school curriculum in Finland, which means that the results of the studies can be directly applied to school practice. 2) There is a clear need for new pedagogical approaches in teaching of electricity, because traditional instruction, such as textbooks and algebraic equations, has been relatively ineffective in promoting students' understanding of electrical circuits (e.g. Frederiksen et al., 1999; McDermott & Shaffer, 1992). Inquiry-learning environments such as laboratories and simulations can enhance instruction and improve students' understanding of electricity, mainly because they provide students with a hands-on opportunity to manipulate circuits and observe and investigate the results of their actions (de Jong, 2006). This opportunity can make the otherwise abstract concepts such as voltage, current, and resistance more tangible, it allows students' to test their own models and thus activates their initial conceptions, and it enables students to build a qualitative understanding of the circuits (see Study II for a more thorough discussion concerning the problems of traditional instruction and the potential benefits of the present inquiry-based learning environments in the domain of electricity). 3) Electricity is well-suited topic for inquiry learning: The laws and basic principles of electrical circuits are not directly visible, but they can be discovered via experimentation.

3.2. Learning environments

This section describes three inquiry-based learning environments in which the students constructed and explored electrical circuits during the interventions. The students worked in pairs in each environment, because working in pairs is a natural procedure in science classrooms in Finland and previous studies have shown that working in pairs can be especially effective when the work involves computers (Lou, Abrami, & d'Apollonia, 2001) or includes complex problem-solving (e.g., Schwartz, 1995).

3.2.1. Laboratory

In the laboratory environment (Studies I and IV), students constructed and inspected real circuits by using a laboratory equipment kit (LEK). The LEK consists of real batteries, wires, bulbs, and a voltmeter. It allowed the students to construct various real DC circuits and conduct electrical measurements. In the LEK, each circuit component is attached to a base that displays the diagrammatic symbol of that component (Figure 1).

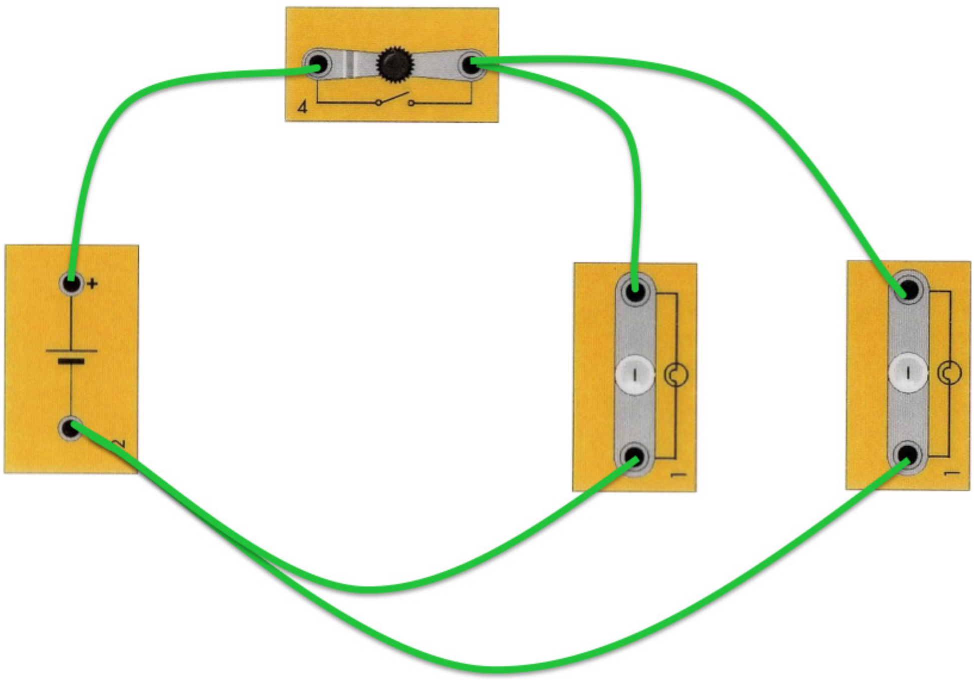

Figure 1. Example of a parallel circuit constructed with the Laboratory Equipment Kit.

3.2.2. Simulation

In the simulation environment (Studies I through IV) students constructed and inspected virtual circuits by using a computer-based simulation called 'Electricity Exploration Tool' (EET; ©Digital Brain, 2003; Figure 2). The representation level of the EET is semi-realistic; it displays circuits schematically, but includes light bulbs with dynamically changing brightness (as the amount of current through the bulb increases, the yellow area inside the bulb becomes larger and the color tone of that yellow changes as well) and realistic measuring devices. The simulated model is authentic with two exceptions: Unlike real circuits the wires have no resistance and the battery is always ideal (i.e. there is no change in the potential difference with time). With the EET, students are able to construct various DC circuits by using the mouse to drag wires and bulbs to the desired location in the circuits. After constructing the circuit or putting the circuit into a particular configuration, students can observe the effects of their actions and get instant feedback. They can, for instance, see what direction and which path(s) the current flows within the circuit (current flow is displayed by static arrows; this is something that cannot be observed in real circuits) and whether the bulbs are lit. They can also conduct electrical measurements with a multimeter by dragging its probes to the required testing points (in the present studies the students were required to measure the voltages across the bulbs in various circuits).

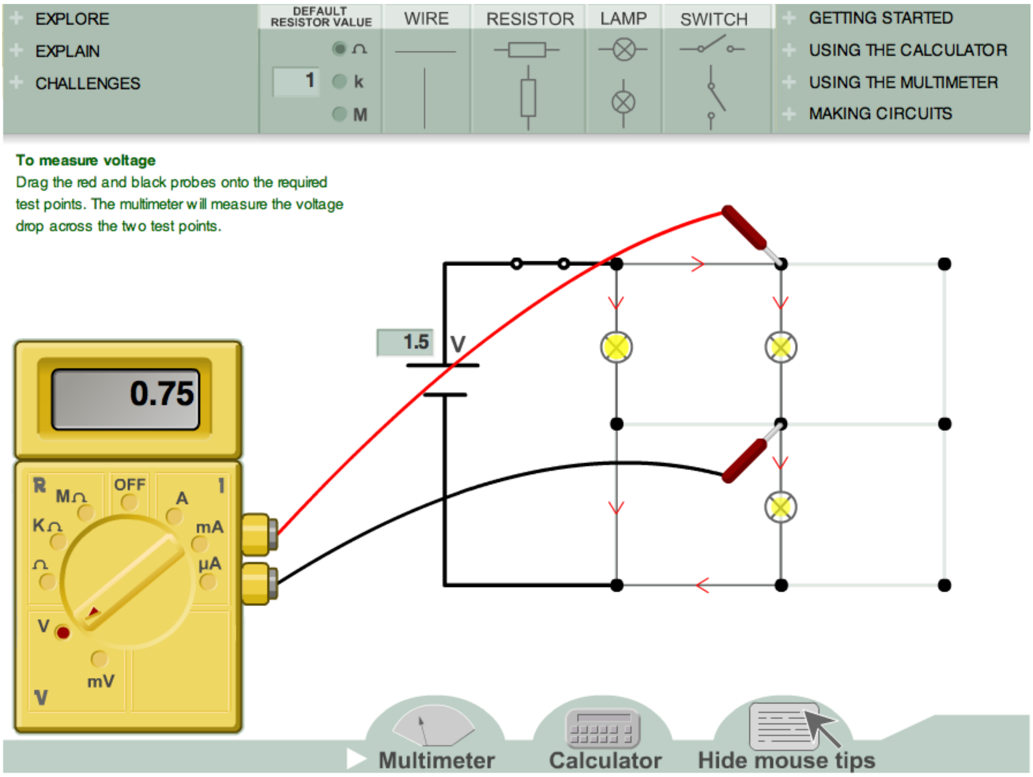

Figure 2. The Electricity Exploration Tool is an easy-to-use simulation for constructing simple DC circuits, observing circuit functionalities, and conducting electrical measurement. Every operation is conducted by dragging or clicking with the mouse.

3.2.3. Simulation-laboratory combination

In the simulation-laboratory combination environment (Studies I through IV) students constructed and inspected both real and virtual circuits, that is, they used the EET and the LEK in parallel. The LEK was placed right next to the computer (the EET). Parallel use means that the students constructed every circuit twice in a row: first using the simulation and then, immediately after succeeding with the simulation, they re-constructed that (same) circuit with the real equipment (circuits) placed next to the computer. It was assumed that having two different representations of electrical circuits available at all times would make it easier for students to learn relevant domain knowledge because those features that are shared across both representations also illustrate/highlight the central structures and principles of the target domain (see sections 1.2.2 through 1.2.5. for more detail). The decision to ask the students to construct each circuit first with the simulation was based on the assumption that constructing virtual circuits is easier than constructing real circuits (cf. Finkelstein et al., 2005), and that the virtual circuit could then serve as a point of reference when the students reconstructed the circuit with the real equipment (cf. Ronen & Eliahu, 2000). In order to make it easier for the students to relate the real circuits (LEK) and the virtual circuits (EET) and make translations from one representation to the other (cf. Ainsworth, 2006), in the LEK, each circuit component was attached to a base that displayed the diagrammatic symbol of that component (see Figure 1), which was almost identical to the symbols used in the EET (Figure 2).

3.3. Design and procedure of experimental studies

Empirical part of the present work consists of the results of two experimental studies. Results of the experiments are analysed and discussed in four empirical studies. This section gives an overview of the basic settings and procedures of both experiments (overview of the four empirical studies are given later in section 4).

3.3.1. Experiment I

Experiment I provides a baseline for my thesis concerning the potential benefits of combining laboratory and simulation activities in science education, as it investigates whether learning in a simulation-laboratory combination environment can enhance students' conceptual understanding of electrical circuits more effectively than learning in a laboratory or simulation environment alone. The sample of the experiment consisted of 66 fourth and fifth grade students (10 to 11 years old; 30 boys and 36 girls). The students constructed and studied electrical circuits in three different inquiry learning environments: laboratory, simulation, and laboratory-simulation combination. The experiment had a one-way (laboratory vs. simulation vs. combination) matched subjects repeated measures (pre-test vs. post-test) ANOVA design.

The students took a pre-test approximately one week before the intervention. The pre-test consisted of two separate tests. The Raven's (1958) Standard Progressive Matrices (RSPM; Sets A through E) test was used to measure students' general learning ability or learning potential, and a subject knowledge assessment questionnaire was used to measure students' initial understanding of electrical circuits. To ensure that all three learning conditions would have the nearest to equal spread of subject knowledge at the baseline[4], students' placement to the learning environments followed the following matching procedure: Sets of three students were matched on pre-test scores. This resulted in total of 22 sets (66 ÷ 3), each set consisting of three students with similar pre-test scores. From each set one student was allocated randomly to one of the three learning environments (see Wallen & Fraenkel, 2001, p. 284, for more details on the matching procedure). After the students were matched

[4] Previous studies have shown that domain-specific prior knowledge (Chambers & Andre, 1997) and general intellectual abilities (e.g. Cohen et al., 1983; von Rhöneck & Grob, 1990) can affect students' learning about basic electricity, and in order to compare the effectiveness of the three learning environments on students' understanding of simple electricity, it was important to control the effects of these two background variables on learning outcomes.

into the conditions, pairs were formed randomly within each condition (each pair worked in the same environment).

During the intervention the pairs in each learning environment had 90 minutes to construct and measure various circuits and investigate circuit's behaviour under different configurations. The laboratory condition worked in their regular classroom where the LEKs were put on the desks. The simulation and combination conditions worked in the school's computer suite. In the combination condition the LEK was placed right next to the computer. It was necessary to structure and scaffold students' inquiry process during the intervention, because research shows unambiguously that unguided inquiry learning is ineffective (Fund, 2007; de Jong & van Joolingen, 1998; Mayer, 2004). In other words, students need help to plan meaningful experimentations and guidance to interpret and reflect obtained experimentation findings (de Jong, 2006). In the experiment, assignments and instructions were given in the form of worksheets. In general, the worksheets asked students to construct various circuits and conduct various electrical measurements with real materials (laboratory condition), with the simulation (simulation condition), or with both real materials and the simulation (combination condition). The worksheets also contained instructional scaffolds that asked students to investigate and infer how the changes and differences in circuit configurations affected circuit behaviour. The students were required to take notes of their observations and then write down their answers on the worksheet. The worksheets were designed to confront common misconceptions of electric circuits that have been identified by a large body of previous studies (e.g. Borges & Gilbert, 1999; McDermott & Shaffer, 1992; Reiner, Slotta, Chi, & Resnick, 2000; Shipstone, 1984) and to correct these misconceptions by gradually introducing the scientific model (in the first step the concept of closed/complete circuit and later on the ohm model). Each worksheet focused on one topic. The worksheets became gradually more difficult. The worksheets began with a very simple task, wherein students were asked to construct a circuit with one battery, wires, and a bulb, and later progressed toward more challenging tasks in which students had to construct circuits containing multiple bulbs.

In order to compare the relative effectiveness of the three learning environments, a post-test that measured changes in students' understanding of electrical circuits was administered one day after the intervention. In order to increase the validity of the interpretations of students' responses to the subject knowledge assessment questionnaire, 20 students were randomly selected for the stimulated recall interview, in which they were asked to explain and justify their answers. Although students worked in pairs during the intervention they completed all the tests individually.

3.3.2. Experiment II

The main aim of Experiment II was to extend Experiment I by exploring whether and how learning outcomes in simulation and simulation-laboratory combination environments are mediated by implicit (only procedural guidance) and explicit (more structure and guidance for the discovery process) instruction in the context of simple DC circuits. A laboratory condition where the students would use the real circuits alone was left out of the design because it was clearly the least effective and the most troublesome learning condition in Experiment I, as well as in some other previous studies (e.g. Finkelstein et al., 2005). The second aim of Experiment II was to investigate whether learning in these environments involves or produces distinctive learning processes that are productive for learners.

The sample of the experiment consisted of 51 fifth and sixth grade students (11 to 12 years old; 31 girls and 20 boys). In the beginning of the intervention the students took a pre-test. The pre-test consisted of a subject knowledge assessment questionnaire that was used to measure student's initial knowledge about the features that affect the lightning and the brightness of the bulb(s) in simple DC circuits.

The study had a 2 (environment: simulation vs. combination) x 2 (instruction: implicit vs. explicit) repeated measures (pre-test vs. post-test) factorial design. Consequently, the students were divided into the following four different learning conditions:

- In the simulation implicit condition (SI), the students used the simulation and received implicit instruction. Implicit instruction means that the students were provided only with procedural guidance, that is, they were told what kind of circuit to construct, how to construct it, and what kind of electrical measurements to conduct.
- In the simulation explicit condition (SE), the students used the simulation and received explicit instruction. Explicit instruction means that in addition to the implicit instruction students were given support and a structure for their inquiry process, that is, when they constructed the circuits they were guided to pay attention to aspects that are important for a theoretical understanding and asked to make comparisons between different circuits.
- In the combination implicit condition (CI), the students used the simulation and the real circuits in parallel and received implicit instruction.
- In the combination explicit condition (CE), the students used the simulation and the real circuits in parallel and received explicit instruction.

Allocation of the students to the above conditions followed the same matching procedure as Experiment I, except the following two issues: 1) as Experiment II included four learning conditions, the unit of a set that was matched on pre-test scores was now four students rather than three. 2) The fact that the sample consisted of an odd number of students and that the number was not directly divisible by the number of conditions meant that two additional steps were needed prior to the actual matching procedure. An odd number of students in the sample meant that not all students could be part of a pair. In order to resolve this issue, a student who had the highest score in the pre-test agreed to work alone during the intervention. Furthermore, as the remaining 50 was still not divisible by four, prior to matching, two randomly selected students were paired and allocated randomly to one of the four learning conditions.

The actual intervention took place about one week after the pre-test. Intervention phase of Experiment II was identical to Experiment I in outline: Students worked in pairs and assignments, and instructions were given in the form of worksheets. As the focus of the study was on the effects that implicit and explicit can have on learning outcomes and processes, the worksheets were designed accordingly. Worksheets with implicit instruction (SI & CI conditions) provided only procedural guidance, that is, they instructed the students what kind of circuit to construct, how to construct it, and what kind of electrical measurements to conduct. Worksheets with explicit instruction (SE & CE) provided, in addition to procedural guidance, structure and metacognitive support for the inquiry process; when the students constructed the circuits they were guided to pay attention to aspects that are important for a theoretical understanding and asked to make comparisons between different circuits. Despite the differences in instructional support between the conditions, the circuits the students were asked to construct and study were identical in all conditions.

Design of the intervention in Experiment II introduced one fundamental departure from the design of Experiment I. In Experiment I the students were given a fixed time to construct and study circuits, whereas in Experiment II they had unlimited time to construct and study a fixed amount of circuits. This change was to ensure that students in each condition would have an equal coverage of the content. Although the use of fixed time is justifiable from the practical point of view—time allocated for lessons in school is typically fixed—it is problematic from the methodological point of view. The problem is that a fixed time situation can confound interpretation of the results, because it easily leads to unequal coverage of content between different conditions. Klahr et al. (2007), for instance, found that in a fixed time situation in the domain of kinetics students were able to carry three times more experiments in a simulation environment than in a laboratory environment. Another departure from Experiment I was that the pairs were working one at a time in the schools' computer suite. This was because each pair was videotaped, in order to capture and analyse students' learning processes in various conditions (Study III).

One day after the intervention each student took a post-test, which was identical to the pre-test. After completing the questionnaire, each student was asked to explain and justify her/his answers in the stimulated recall interview, in order to increase the validity of the interpretations of students' responses to the subject knowledge assessment questionnaire. As in Experiment I, students completed all the tests individually.

In both experiments, several actions were taken in order to control the effects that some intervening variables could have on the results of the experiments. For instance, in each study the same teacher taught the students in all conditions, in order to control for a possible teacher effect. A general introduction to the domain of electricity that was given in the beginning of each intervention was identical in all conditions. Worksheets that gave the assignments and instructions for the students during the intervention were designed to be as equal as possible between the conditions. For instance, each circuit and circuit component in the worksheets was always depicted as a picture that corresponded to the real circuits the students used in laboratory and combination environments as well as a picture that corresponded to the virtual circuits the students used in simulation and combination environments.

3.4. Assessment of learning

3.4.1. Learning outcomes

In both experiments students completed a subject knowledge assessment questionnaire before and after they constructed circuits. The questionnaire was used to measure learning outcomes in different learning conditions and compare the outcomes between the conditions. In the pre-test, the questionnaire was used to measure students' initial understanding of the features that affect the functioning and the brightness of the bulb(s) in simple DC circuits, and in the post-test, the questionnaire measured changes in students' knowledge about the same topics. In Experiment II, for instance, the pre-test questionnaire consisted of five questions that included multiple items (total of 15 items). The first question measured students' understanding of the concept of a closed circuit. For the first question, the students were asked to evaluate different circuit configurations and decide whether the bulb would light or not. In order to be successful, they needed to understand that there are two polarities associated with the electrical force supplied by a battery, and that, for this electrical force to be applied to a resistor (bulb), both polarities must be connected, one to each of the terminals of the device. In the second question, the students were asked to indicate how they thought current flows through the circuit. Here they needed to know that, once a circuit is closed, the current circulates in a given direction, and that the current flow between the voltage source and the devices connected to the circuit is uniform and continual. The remaining three questions measured students' understanding of how different circuit configurations affect bulb brightness. The third question asked students to rank five identical bulbs according to their relative brightness. Regardless of whether a battery is perceived as ideal or real, the relative brightness remains the same. To solve this question, no calculations were required. It was sufficient to think in terms of a simple qualitative model in which the circuit configuration determines the magnitude of the voltage across circuit components. This assignment was originally used by McDermott and Shaffer (1992), and has been found to be very effective in discriminating between students who understand the principles behind the DC circuits and those who do not. In the fourth question, the students were asked to calculate the voltages of each of the bulbs in question 3. The task required only the most elementary mathematical skills, as a 2-V battery was chosen to make calculations easy. In the fifth question, the students were asked to alter bulb brightness by reconfiguring the circuits. Although this question was primarily designed to measure students' understanding of series and parallel circuits, it also provided further information on their conception of closed circuits (e.g., if they drew only one wire from either of the battery terminals to the bulb, this would tell us that the student believed this to be sufficient to light the bulb). In both experiments, the subject knowledge assessment questionnaire in the post-test included the same items as in the pre-test, but it also included some additional items that included more complex circuits.

Students' answers to the Subject Knowledge Assessment Questionnaire were analysed on two levels:

Quantitative level. Students' answers to all items in the subject knowledge assessment questionnaire were scored against the model answer template. From 0.5 to 1 (depending on the estimated item difficulty) a point was given for a correct answer and 0 for an incorrect answer. Cronbach's (1951) alpha for the questionnaire was calculated only in Experiment II, which showed that the reliability of the questionnaire was good: pretest $\alpha = 0.667$; posttest $\alpha = 0.822$. The lower alpha level in the pre-test was expected because this was the student's first formal introduction to the subject of electricity, and prior to the intervention the students' knowledge on electricity was less accurate and systematic than after the intervention.

Conceptual level. In order to obtain deeper insight into students' conceptual understanding of simple DC circuits in different learning conditions, students' answers to the subject knowledge assessment questionnaire were also analysed on a qualitative level, and were then classified into conceptual categories that characterised the qualitatively different mental models with which students understood simple DC circuits. Data from the stimulated recall interviews served as validity confirmation for the qualitative analysis. Extensive research conducted by Kärrqvist (1985), McDermott (McDermott & Shaffer, 1992), Osborne (1983), and Shipstone (1984) on students' mental models of electricity served as a starting point for the qualitative categorisation (see also e.g., Borges & Gilbert, 1999; Reiner et al., 2000; Sencar & Eryılmaz, 2004, for reviews on students' mental models about electricity). Two independent raters conducted the qualitative analysis with an inter-rater reliability (Cohen's kappa) of 0.89 in Experiment I and 0.91 in Experiment II. Disagreements between the raters tended to arise from the fact that some of the weaker students, in particular, constantly changed their reasoning pattern to suit the question in hand; thus their reasoning did not consistently follow any single principle (see also McDermott & Shaffer, 1992; Planinic, Boone, Krsnik & Beilfuss, 2006; Shepardson & Moje, 1999). The disagreements were discussed until agreement was reached.

3.4.2. Learning efficiency

Learning efficiency was determined for each participant through his/her gain in subject knowledge from the subject knowledge pre-test to the post-test divided by the time in minutes he/she spent on the circuits and worksheets during the intervention.

In Experiment II it was expected that the coverage of the material would take more time in certain conditions than in others because the students had unlimited time to construct and study a fixed number of circuits. Consequently, in Experiment II learning was analysed not only in terms of learning outcome, but also in terms of learning efficiency. When we analyse learning outcomes, the underlying question is whether certain instructional conditions will stimulate more elaborate cognitive processing and, therefore, result in better learning outcomes. When we analyse learning efficiency, we ask how well the effort and the processing stimulated by each instructional condition translate to learning outcomes (Rasch & Schnotz, 2009). For instance, it was expected that using the simulation and the real circuits in combination will stimulate more elaborate cognitive processing than using the simulation alone, thus resulting in a better understanding of electrical circuits. However, it was also expected that the combination will be more time-consuming (i.e. require more effort than using the simulation alone). In a similar fashion, it was expected that explicit instruction will stimulate more elaborate cognitive processing as well as increase learning time, as compared to implicit instruction. From the point of view of learning efficiency, the question is, do the additional learning outcomes compensate the additional effort? For instance, if the combination takes only slightly more time than the simulation or if the explicit instruction takes only slightly more time than the implicit instruction, but it yields considerably better learning outcomes, then the combination or/and explicit instruction should be preferred. Instead, if the learning outcomes are only slightly better in the combination or with the explicit instruction but take considerably more time than the simulation alone or with the implicit instruction, one might opt for the latter because of higher efficiency.

3.4.3. Learning processes

In Experiment II the work of all 25 pairs was video recorded during the intervention. One video-recording device captured the action on a computer screen and the other recorded students' actions, expressions, and talk. These two video streams were combined into one video output layer in order to synchronize students' reactions with the related situation. A detailed transcript of each videotape was constructed. This included students' conversational interactions, their answers to the worksheets, and their non-verbal interactions with the simulation and the laboratory equipment kit. A method of content analysis was used to analyse the video data and video data transcripts. The focus of the analysis was on cognitive conflicts, self-explanations, and analogical encodings. Two independent raters rated 20 percent of the video data concerning cognitive conflicts and self-explanations.

Cognitive conflict: An incident was categorised as a cognitive conflict if a student explicitly expressed disbelief in the results of the simulation or real circuits and searched for an explanation for the discrepancy between their expectations and the results. A situation in which a student was first surprised by the results of the simulation or real circuits, but accepted the new result immediately, or paid no additional attention to the matter, was *not* categorised as cognitive conflict. Inter-rater reliability (Cohen's kappa) for cognitive conflicts was .88.

The aim here was to investigate if simultaneous use of simulations and laboratories can increase students' sensitivity to novel findings and the richer external support afforded by the combination environment can result in the use of more adequate strategies to deal with the conflict as compared to using a simulation alone. In line with Piagetian theory, many authors have proposed that cognitive conflict between prior knowledge and the requirements of new tasks can be a fundamental driving force in learning scientific concepts (e.g., Chinn & Brewer, 1993; Strike & Posner, 1982), though it is also acknowledged that cognitive conflict introduced by pedagogical arrangements is often insufficient alone to promote conceptual change and conceptual learning in general (Limon, 2001).

Self-explanation: A comment or a comment chain that contained domain-relevant articulation concerning the behaviour of a particular virtual or real circuit was categorised as a self-explanation. Inter-rater reliability for self-explanations was .88.

The aim here was to investigate if the opportunity to move between two external representations in the combination environment elicits self-explanations more effectively than the use of single external representation in the simulation environment, and/or if the incidence of self-explanation can also be increased by explicit guidance to look for explanations as compared to implicit instruction with no specific prompts. Self-explanations may be a factor that helps students' conceptual understanding. In their study on problem solving in physics, Chi and VanLehn (1991) found that good solvers provided more self-explanations during the problem-solving process. They defined self-explanations as comments that pertained to the content of physics. Self-explanations are generated in the context of learning something new.

Analogical encoding: The analysis focused on the use of the simulation and the real circuits in parallel in the combination environment. Analogical encoding was defined as an event where the students linked and made explicit translations between the simulation and the real circuits (thus, analogical encoding can take place only in the combination environment).

The aim was to explore if analogical encoding as a whole takes place in combination environment, and investigate if and how students can benefit from such situations in the domain of electricity. Because the aim was to only search illustrative examples of the situations where analogical encodings took place (i.e. to prove that analogical encoding exist in the present context) and examine such situations, instances of analogical encodings were not categorised or quantified. As it has been noted earlier, several studies have found that analogical encoding, that is, comparing two instances of a to-be-learned principle, can be a powerful means of promoting learning, even for novices, because the comparison process seems to promote schema abstraction and deeper understanding of the underlying mechanisms and principles.

It should be noted that there were some problems related to the video data. Sometimes the students were only whispering (although they were encouraged to speak at a normal conversation level), so it was impossible to make sense of the conversation. Although in most of the cases both the video and the audio were flawless, there were also some minor technical problems in the data: The audio or the video or both were sometimes momentarily disrupted (typically one to three seconds). The worst case was in the combination implicit condition where almost half of one video and audio was corrupted (this was the only incidence with such a large data loss).

3.5. Statistical methods and analyses

Several different kinds of statistical analyses were used in the present set of four studies to analyse the data of the two experiments.

Cronbach's (1951) alpha was used to estimate the reliability of the subject knowledge assessment questionnaire (Study II). Cohen's kappa was used as an estimate for inter-rater reliability of categorisations of conceptual models (Studies I and II) and learning processes (Study III).

Subject knowledge pre-test scores of each condition were compared with one-way ANOVA, in order to ensure that the conditions had sufficiently equal levels and spread of subject knowledge at the baseline. After that, a within-subjects repeated measures ANOVAs of pre-test and post-test was run independently for each condition in order to establish learning effects. Cohen's (1988, p. 48) standardised mean difference effect size (d) for one sample paired observations, which expresses pre- and post-test mean difference in standard deviation units, was reported as an indicator for the size of the learning effect in each condition (Studies I and II). For analysing developmental differences between conditions, ANCOVA, with subject knowledge pre-test score as a covariate, was run together with Bonferroni corrected post-hoc comparisons (Study I) and planned contrast (Study II). Post-test mean differences between the condition were also reported and expressed in standard deviation units with 95% confidence intervals, this time using Hedges' (1981) bias corrected standardised mean difference effect size (g) for two independent samples. In Study I, students' conceptual development in various conditions was compared using Chi Square (χ^2) test, but this approach was abandoned in Study II due to the test's low statistical power to detect differences.

Analysis of regression was used to justify the use of covariates by (a) examining the relationship between pre-test variables (subject knowledge and general learning potential) and post-test scores and by (b) making sure that the slopes between covariate(s) and post-test scores were homogenous across all conditions (Studies I and II).

In order to aggregate the post-test results from Experiment I and Experiment II and analyse the overall effect of the parameters that were identical across the experiments, a meta-analytic technique called Stouffer method (Mosteller & Bush, 1954; Rosenthal, 1984) was used to average p-values and effect sizes from both experiments (Study IV).

Kruskall-Wallis' ANOVA was used to analyse differences in the amount of self-explanations between conditions (Study III). Use of non-parametric test was necessary here because the distributions of self-explanations were heavily skewed in all conditions; out of the total of 50 students, there were 14 students who did not provide a single self-explanation during the intervention, and 11 students provided only one self-explanation.

4. An overview of the empirical studies

4.1. Study I

Jaakkola, T. & Nurmi, S. (2008). Fostering Elementary School Students' Understanding of Simple Electricity by Combining Simulation and Laboratory Activities. *Journal of Computer Assisted Learning*, 24(4), 271-283.

Computer simulations and laboratory activities have been traditionally treated as substitute or competing methods in science teaching. The aim of this experimental study was to investigate if it would be more beneficial to combine simulation and laboratory activities than to use them separately in teaching the basics of simple electricity. In order to achieve this, the study analysed learning outcomes in Experiment I (section 3.2.1) that had a one-way (laboratory vs. simulation vs. combination) matched subjects repeated measures (pre-test vs. post-test) ANOVA design.

The initial sample consisted of 66 fourth and fifth grade students (10 to 11 years old; 30 boys and 36 girls) from one urban Finnish elementary school, but two students had to pull owing to illness. The students had not had any previous formal education in electricity.

The participants took a pre-test approximately one week before the intervention. The pre-test consisted of two separate tests, both of which students completed individually. The Raven's (1958) Standard Progressive Matrices (Sets A through E) test was used to measure students' general educative ability. A subject knowledge assessment questionnaire was used to measure students' initial understanding of simple series and parallel circuits. Sets of three students were matched on pre-test scores and from each set the students were allocated randomly into one of the following three experimental conditions (see Section 3.3.1. for more details on the matching procedure):

- In laboratory condition students constructed and inspected real circuits.
- In simulation condition students constructed and inspected virtual circuits.
- In simulation-laboratory combination condition students used real and virtual circuits simultaneously.

The actual intervention, where students worked in one of the above conditions, lasted 90 minutes (two consecutive school hours). In the beginning of the intervention, students received a 15-minute general introduction to the subject of electricity. This introduction was identical in all three learning environments. After the introduction, students worked in pairs with various circuit assignments. Working in pairs is a natural procedure in science classrooms in Finland, and previous studies have shown the benefits of collaboration in computer and problem-solving contexts. The assignments were given in worksheets that guided students to construct various circuits and conduct electrical measurements and provided scaffolds for making proper inferences. The worksheets began with a very simple task, wherein students were asked to construct a (closed) single bulb circuit, and continued with more challenging tasks in which students had to construct circuits containing multiple bulbs. In order to treat the learning environments equally, each representation of a circuit in the worksheets was duplicated: One representation corresponded to real circuit and the other corresponded to virtual circuit.

A post-test, which students completed individually, was administered one day after the intervention. It consisted of a subject knowledge assessment questionnaire that included all the items of the subject knowledge assessment questionnaire in the pre-test, plus seven additional items with more complex circuits. The questionnaire measured changes in students' knowledge about simple series and parallel circuits, and it was used as an instrument to compare the relative effectiveness of the three learning environments. After completing the post-test questionnaire, 20 randomly selected students were asked to explain and justify her/his answers in the stimulated recall interview, in order to increase the validity of our interpretations of students' responses to the questionnaire.

Students' answers to the Raven's test were scored with the official scoring key. Answers to the subject knowledge assessment questionnaire were first scored quantitatively against the model answer template, and then analysed qualitatively by two independent raters, in order to obtain a deeper insight into students' conceptual understanding of simple electric circuits in different learning environments.

The results showed that studying in the simulation–laboratory combination environment led to statistically better understanding of the circuits in the post-test than studying in either laboratory or simulation environment alone. Students in the simulation condition also made clear progress during the intervention, but their understanding did not reach the level of the combined condition in the post-test. The progress was most modest in the laboratory condition where the students' conceptual understanding remained at an elementary level after the intervention. However, the difference(s) between the simulation and the laboratory environments was not statistically significant. The results highlight the benefits of using simulation along with hands-on laboratory activities to promote students' understanding of electricity.

4.2. Study II

Jaakkola, T., Nurmi, S. & Veermans, K. (2011). A comparison of students' conceptual understanding of electric circuits in simulation only and simulation-laboratory contexts. *Journal of Research in Science Teaching*, 48(1), 71-93.

Research shows unambiguously that students need structure and guidance for their inquiry process in order to benefit from inquiry learning opportunities (Fund, 2007; de Jong, 2006; Mayer, 2004). However, it is unclear what constitutes sufficient or optimal support for the inquiry process. It is evident that if inquiry learning environments do not provide sufficient scaffolding, academically weaker students will very likely get frustrated and fail. On the other hand, if learning environments provide students too much scaffolding or too much information prematurely, they may not be able to learn proper knowledge because they do not exert enough cognitive efforts (Kapur, 2008; Schmidt & Bjork, 1992).

The aim of this study was to investigate the above challenge by exploring whether and how learning outcomes in simulation and simulation-laboratory combination environments are mediated by implicit (only procedural guidance) and explicit (more structure and guidance for the discovery process) instruction in the context of simple DC circuits. The study analyses data concerning learning outcomes in Experiment II (Section 3.3.2).

The sample consisted of 50 fifth and sixth grade students (11 to 12 years old; 31 girls and 19 boys) from one urban Finnish elementary school; the initial sample consisted of 51 students, but one student was excluded from the analyses because he was left without a pair due to an odd number of participants (rationale for working in pairs was given previously, in Study I overview and in section 3.2.).

The study had a 2 (environment: simulation vs. combination) x 2 (instruction: implicit vs. explicit) repeated measures (pre-test vs. post-test) factorial design. The participants took a pre-test approximately one week before the intervention. The pre-test consisted of a subject knowledge assessment questionnaire that was used to measure students' initial knowledge about the features that affect the lightning and the brightness of the bulb(s) in simple DC circuits. As in Study I, sets of students were matched on pre-test scores and then allocated randomly to one of the following four learning conditions:

- In the simulation implicit condition (SI), the students used the simulation and received implicit instruction.
- In the simulation explicit condition (SE), the students used the simulation and received explicit instruction.
- In the combination implicit condition (CI), the students used the simulation and the real circuits in parallel and received implicit instruction.
- In the combination explicit condition (CE), the students used the simulation and the real circuits in parallel and received explicit instruction.

The students worked in one of the above conditions during the intervention. A laboratory condition where the students would use the real circuits alone was left out of the design because it was clearly the least effective and the most troublesome learning condition in Study I as well as in some other previous studies. Intervention phase of Experiment II was identical to Experiment I in outline: Students worked in pairs, and assignments and instructions were given in the form of worksheets. However, as the focus of the study was on the effects that implicit and explicit instruction can have on learning outcomes and processes, the worksheets were designed accordingly. Worksheets with implicit instruction (SI and CI conditions) provided only procedural guidance, whereas worksheets with explicit instruction (SE and CE) provided, in addition to procedural guidance, metacognitive support for interpreting the results of the experimentation. Despite the differences in instructional support between the conditions, the circuits the students were asked to construct and study were identical in all conditions. Design of the intervention in Experiment II introduced one fundamental departure from the design of Experiment I. In Experiment I the students were given a fixed time to construct and study circuits, whereas in Experiment II they had an unlimited time to construct and study a fixed amount of circuits. This change was to ensure that students in each condition would have an equal coverage of the content (see section 3.3.2 for the rationale). Another departure from Experiment I was that the pairs were working one at a time in the schools' computer suite. This was because each pair was videotaped, in order to capture and analyse students' learning processes in various conditions (Study III).

One day after the intervention each student took a post-test, which was identical to the pre-test. After completing the questionnaire, the students were asked to explain and justify their answers in the stimulated recall interview, in order to increase the validity of the interpretations of students' responses to the subject knowledge assessment questionnaire. Although students worked in pairs during the intervention, they completed all the tests individually.

Students' answers to the subject knowledge assessment questionnaire were first scored quantitatively against the model answer template, and then analysed qualitatively by two independent raters, in order to obtain a deeper insight into students' conceptual understanding of simple electric circuits in different learning environments.

The results demonstrated that the instructional support had an expected effect on students' understanding of electric circuits when they used the simulation alone; pure procedural guidance (SI) was insufficient to promote conceptual understanding, but when the students were given explicit guidance for the discovery process (SE) they were able to gain a significant amount of subject knowledge. However, this additional scaffolding was not enough to reach the level of the students in the combination environment (CI and CE). A surprising finding was that instructional support had a different effect in the combination environment than in the simulation environment. In the combination environment explicit instruction (CE) did not seem to elicit much additional gain for students' understanding of electric circuits compared to implicit instruction (CI). Instead, explicit instruction slowed down the inquiry process substantially in the combination environment. These results suggest, in accordance with the finding of Study I, that when teaching students about electricity, the students can gain better understanding when they have an opportunity to use the simulation and the real circuits in parallel than if they have only a computer simulation available, even when the use of the simulation is supported with the explicit instruction.

4.3. Study III

Jaakkola, T., Nurmi, S. & Lehtinen, E. (2010). Conceptual change in learning electricity: using virtual and concrete external representations simultaneously. In L. Verschaffel, E. De Corte, T. de Jong & J. Elen (Eds.) Use of representations in reasoning and problem solving. Analysis and improvement. New Perspectives in Learning and Instruction Series (pp. 133-152). NY: Routledge.

This study analyzed from video data learning processes of those 50 students that participated in experiment II (cf. Study II above). The aim of the study was to find out possible explanations for the success of the combination condition in Experiments I and II. The focus was on three specific learning processes: cognitive conflicts, self-explanations, and analogical encodings.

During the intervention phase of Experiment II, student pairs were working one at a time in the schools' computer suite. Each pair was videotaped. One video-recording device captured the action on a computer screen and the other recorded student's actions, expressions, and talk. These two video streams were combined into one video output layer in order to synchronize students' reactions with the related situation. A detailed transcript of each recording was constructed. This included students' conversational interactions, their answers to the worksheets, and their non-verbal interactions with the simulation and the laboratory. A method of content analysis was used to analyse the video data and video data transcripts. The focus of the analysis was on cognitive conflicts, self-explanations, and analogical encodings. The data concerning cognitive conflicts and self-explanations was categorised and quantified. Two independent raters rated 20 % of the video data concerning cognitive conflicts and self-explanations. An incident was categorised as a cognitive conflict if a student explicitly expressed disbelief in the results of the simulation or real circuits and searched for an explanation for the discrepancy between their expectations and the results.

A comment or a comment chain that contained domain-relevant articulation concerning the behaviour of a particular virtual or real circuit was categorised as a self-explanation. Analogical encoding was defined as an event in which the students linked and made explicit translations between the simulation and the real circuits. Because there was no attempt to compare any conditions (analogical encoding can take place only in the combination condition), instances of analogical encodings were not categorised nor quantified.

The video data provided clear evidence about the existence and the benefits of analogical encodings in the combination environment. The students clearly benefited from the fact that they could compare simultaneously virtual and real circuits. In some cases analogical encoding between two representations enabled students to gain deeper and more generalised understanding when they discovered that the same rule applied to both representations; in other cases one of the representations served as a point of reference that helped and guided students to interpret and understand the second representation. The results showed no differences in the amount of cognitive conflicts and self-explanations between the combination and simulation conditions, thus ruling out the possibility that these two factors could explain the success and superiority of students using simulations and laboratories together. On the other hand, a nascent trend suggesting that those students who used the combination seemed to generate more self-explanations than the students who used only the simulation was observed among those students who received only implicit instruction (CI vs. SI; cf. Study II above). Overall the amount of cognitive conflicts was lower than expected—in all conditions only about a quarter of the students experienced a conflict and only one student experienced more than one conflict. This finding suggests that it can be beneficial to try to promote students' conceptual understanding of electrical circuits at the early elementary school level because they do not yet have deeply rooted misconceptions that could hamper teaching and learning, as is often the challenge with more experienced learners.

4.4. Study IV

Jaakkola, T. & Nurmi, S. (2008). Instructional Effectiveness of Learning Objects. In L. Lockyer, S. Bennett, S. Agostinho & B. Harper (eds.) *Handbook of Research on Learning Design and Learning Objects: Issues, Applications and Technologies* (pp. 532-552). New York: Information Science Reference.

The main aim of the Study IV was to obtain an aggregated overview of the learning outcomes of Studies I and II (or Experiments I and II), that is, to investigate the relative effectiveness of laboratories, simulations, and simulation-laboratory combination when the results of Studies I and II are combined. Instead of focusing only on the results of individual studies, it is more beneficial to investigate the impact of identical parameters across the studies simultaneously: By combining the results from individual studies we increase the sample size, which allows us to make firmer conclusions and detect more easily statistical differences. The second aim of the Study IV was to explore the relationship between the learning environments and students' prior knowledge, that is, whether laboratory, simulation, and laboratory-simulation environments have specific learning impact among students with low or high prior domain knowledge.

The results from Studies I and II were combined and analysed using common meta-analytic techniques. As far as the main aim is concerned, the results showed that the students in the simulation-laboratory combination environments outperformed the students working only in the laboratory environment and those working only in the simulation environment. The margin by which the students in the combination environment outperformed the students in the laboratory environment was large: 91% of the students studying electricity in the combination environment did better in the post-test than the average student in the laboratory environment. The magnitude of the effect by which the students in the combination environment outperformed the students in the simulation environment was between medium and large: 76% of the students in the combination environment did better than the average student in the simulation environment. Seventy percent of the students in the simulation environment did better in the post-test than the average students in the laboratory environment. However, this result has to be treated as approximate and it needs further verification, as the difference between the two conditions did not reach the level of statistical significance.

The aggregated results further showed that, overall, students seemed to benefit from combining simulations and laboratories regardless of their level of prior knowledge, that is, students with either low or high prior knowledge who studied circuits in the combination environment outperformed their counterparts who studied in the laboratory or simulation environment alone. The effect seemed to be slightly bigger among the students with low prior knowledge. However, more detailed inspection of the results showed that there were considerable differences between the studies regarding how students with low and high prior knowledge benefited from the combination: In Study I, especially students with low prior knowledge benefited from the combination as compared to those students who used only the simulation, whereas in Study II, only students with high prior knowledge seemed to benefit from the combination relative to the simulation group. Regarding the differences between simulation and laboratory groups, the benefits of using a simulation seemed to be slightly higher among students with high prior knowledge.

Study IV also included results from two additional studies that were conducted in a drill-and-practice context and in different domains (language and mathematics: grammar and fractions). In these studies, the learning outcomes of those students who studied in a computer-based learning environment were contrasted with the outcomes of those who studied the topics in a more traditional paper-and-pencil context. Aggregated results of these studies showed that higher learning outcomes were gained in the paper-and-pencil environment. These results suggest that inclusion of computer-based instruction seems to fit better in inquiry contexts than in drill-and-practice contexts.

5. Main findings and discussion

The focus of the present work was on 10- to 12-year-old elementary school students' conceptual learning outcomes in science in two specific inquiry-learning environments, laboratory and simulation. The main aim was to examine if it would be more beneficial to combine than contrast simulation and laboratory activities in science teaching. In the introduction it was argued that the status quo where laboratories and simulations are seen as alternative or competing methods in science teaching is hardly an optimal solution to promote students' learning and understanding in various science domains. It was hypothesised that it would make more sense and be more productive to combine laboratories and simulations. Several explanations and examples were provided to back up the hypothesis.

In order to test whether learning with the combination of laboratory and simulation activities can result in better conceptual understanding in science than learning with laboratory or simulation activities alone, two experiments were conducted in the domain of electricity. In these experiments students constructed and studied electrical circuits in three different learning environments: laboratory (real circuits), simulation (virtual circuits), and simulation-laboratory combination (real and virtual circuits were used simultaneously). The results of the experiments were presented in four empirical studies. Three of the studies focused on learning outcomes between the conditions and one on learning processes.

The results of the four empirical studies provide clear support for the hypothesis concerning the (additional) benefits of combining laboratories and simulations. The results of Study I showed that studying electrical circuits in the simulation–laboratory combination environment improved students' conceptual understanding of electrical circuits more than studying circuits in simulation and laboratory environments alone. Although there were no statistical differences between simulation and laboratory environments, the learning effect was more pronounced in the simulation condition where the students made clear progress during the intervention, whereas in the laboratory condition students' conceptual understanding remained at an elementary level after the intervention. In Study II it was observed that when the students were working with the simulation alone, they were able to gain a significantly greater amount of subject knowledge when they received metacognitive support (explicit instruction) for the discovery process than when they received only procedural guidance (implicit instruction). However, this additional scaffolding was not enough to reach the level of the students in the combination environment. A surprising finding in Study II was that instructional support had a different effect in the combination environment than in the simulation environment. In the combination environment explicit instruction did not seem to elicit much additional gain for students' understanding of electric circuits compared to implicit instruction. Instead, explicit instruction slowed down the inquiry process substantially in the combination environment. In other words, it could be concluded that explicit instruction was not beneficial or harmful for the learning outcomes in the combination environment, but it reduced learning efficiency considerably. Aggregated results (Study IV) of Studies I and II showed that on average, 91% of the students in the combination environment scored above the average of the laboratory environment, and 76% of them scored also above the average of the simulation environment. Seventy percent of the students in the simulation environment scored above the average of the laboratory environment. These results highlight the benefits of using simulation along with hands-on laboratory activities to promote students' understanding of electricity. It can be concluded that when teaching students about electricity, the students can gain better understanding when they have an opportunity to use the simulation and the real circuits in parallel than if they have only the real circuits or only a computer simulation available, even when the use of the simulation is supported with the explicit instruction.

Study III investigated from video data learning processes in simulation and simulation-laboratory combination environments, in order to find out possible explanations for the success of the combination. The video data provided clear evidence about the benefits of studying with and from two different but overlapping external representations simultaneously. Mostly the representations complemented each other, that is, one representation helped students to interpret and understand the outcomes they received from the other representation. However, there were also instances in which analogical encoding took place, that is, situations in which the slightly discrepant results between the representations 'forced' students to focus on those features that could be generalised across the two representations. No statistical differences were found in the amount of experienced cognitive conflicts and self-explanations between simulation and combination conditions, though in self-explanations there was a nascent trend in favour of the combination. There was also a clear tendency suggesting that explicit guidance increased the amount of self-explanations. Overall, the amount of cognitive conflicts and self-explanations was very low.

5.1. Theoretical implications

The results of the empirical studies have important theoretical implications for science teaching literature. The results extend current understanding of how to use laboratories and simulations effectively in science teaching. Laboratories and simulations have been traditionally considered as competing and mutually exclusive methods in science teaching. However, the results of the present empirical studies suggest that it is more beneficial to combine than contrast laboratory activities in science teaching, as the combination of simulation and laboratory activities can promote students' conceptual understanding more effectively than laboratories and simulations alone. In other words, laboratories and simulations should be treated and used in science education as representations that complement one another and help students to gain better understanding of scientific concepts and phenomena.

There have been other attempts to examine the potential of combining laboratories and simulation in science teaching (Campbell et al. 2002; Ronen & Eliahu, 2000; Zacharia, 2007; Zacharia et al., 2008), but these studies have suffered from methodological shortcomings that have left plenty of room for alternative explanations. For instance, none of the studies included a 'pure' simulation condition as a control for the combination condition. Consequently, it is impossible to judge whether it was the combination of laboratory and simulation activities or merely the simulation that caused the positive learning effect in these studies. Furthermore, this defect prevented the studies from assessing the effectiveness of the combination relative to using a simulation alone. The design of Study I included both 'pure' laboratory and 'pure' simulation conditions as controls for the combination condition. Consequently, the outcomes of Study I can be considered as the first unambiguous evidence on the benefits of combining laboratory and simulation activities in science education as compared to learning with laboratories and simulations alone.

Investigation of students' learning processes in Study III was able to identify particular learning mechanisms that can explain why learners benefited from the combination learning environment. Mostly the two representations complemented each other, that is, one representation helped students to interpret and understand the outcomes they received from the other representation (Ainsworth, 2006; Kurtz et al., 2001). However, there were also instances where analogical encoding took place, that is, situations were the slightly discrepant results between the representations 'forced' students to focus on those features that could be generalised across the two representations (Gentner et al., 2003; Thompson, et al., 2000). There is also a reason to assume that the success of some students in the combination environment was not based so much on the interaction and encoding between two representations, as it was based on the constant availability of both representations, which ensured that the students could always learn with their preferred representation (Tabachnek-Schijf & Simon, 1998). Furthermore, there was no evidence that the success of the combination environment would be due to mistrust concerning the authenticity or the trustworthiness of the simulation (cf. Hennessy & O'Shea, 1993; Ronen & Eliahu, 2000; Srinivasan et al., 2006). In other words, there is no evidence that the students in the combination environment outperformed the students in the simulation environment because they could test with real equipment that the laws and principles of simulation also apply in reality. Overall, only a few students experienced any kind of cognitive conflicts during the interventions phase, and except one occasion (excerpt 1 in Study III), none of the conflicts were explicitly related to the functioning of the simulation itself. Had there been a trust issue, many more simulation related cognitive conflicts should have taken place.

Finally, the results also extend current understanding of learning with multiple representations. Previous studies concerning learning with multiple representations have involved invariably older students; the present research has shown that use of multiple representations can be beneficial even among elementary school students with no prior formal experiences in the target domain. To paraphrase Gentner and her colleagues (2003), present findings suggest that learning with and from multiple representations can be illuminating even among completely novice students and in situations when neither of the representations is well understood. Furthermore, the present results also suggest that the theories of learning with multiple representations, which originate from the research that has invariably involved learning from text and pictorial representations (e.g. Gentner et al., 2003; Gick & Holyoak, 1983; Kalyuga et al., 1998; Kollofel et al., 2009; Rasch & Schnotz, 2009), can be generalised to other type of learning environments as well.

5.2. Practical implications

The results of the four empirical studies have important implications for practice. First and foremost, the present results suggest that when teaching students about electricity, the students can gain better understanding when they have an opportunity to use the simulation and the real circuits in parallel than if they have only real circuits or a computer simulation available. It is reasonable to assume that this recommendation can be applied to other science domains as well (cf. Zacharia et al., 2008).

If a teacher needs to make a choice between a simulation and real circuits and his/her aim is to improve students' conceptual understanding, there are multiple reasons to select a simulation. Review of various empirical findings in chapter 1 showed rather unanimously that learning with simulations produces at the minimum equal and occasionally even better learning outcomes as compared to learning with real equipment. Although Study I was unable to detect statistical differences between laboratory and simulation conditions, the learning effect was still more pronounced in the latter condition. During the intervention of Study I, it was observed that students also encountered more problems in the laboratory condition. Similar problems have been also reported in other studies (e.g. Finkelstein et al., 2005). Virtual learning environments offer also practical advantages over laboratories (cf. Klahr et al., 2007).

Simulations are suitable for young and inexperienced learners. The participants of the empirical studies were elementary school students with no prior formal experiences with electrical circuits. As the overall learning gains in the simulation environments were positive, it can be concluded that simulations are suitable even for young and inexperienced students. However, the effectiveness of simulations can be increased by conducting simultaneously corresponding experiments with real equipment. In the case where only a simulation is available, teachers should pay careful attention to the design of the instructional support. Pure procedural support is insufficient to promote learning of conceptual knowledge; the students should also be guided in terms of what they should focus on (cf. de Jong, 2006; de Jong & van Joolingen, 1998).

It can be beneficial to try to promote students' conceptual understanding of electrical circuits at the early elementary school level because they do not yet have deeply-rooted misconceptions that could hamper teaching and learning. Results of Study III showed that students' overall resistance to change was relatively low because this was their first formal introduction to electric circuits and their initial models concerning electrical circuits were mostly immature and fragmentary. The fragmented nature (cf. diSessa, 1993) of the students' initial models in the present study becomes evident when we look at the reliability of the subject knowledge assessment questionnaire in Study II: Cronbach's alpha for the pre- and post-test was .667 and .822, respectively. The lower pre-test alpha level means that the students' knowledge of electricity was less accurate and systematic before the intervention than after the intervention. In other words, at this early stage of science learning, the students seem to have some correct prior knowledge about the functioning of electrical circuits, but that knowledge is incomplete. Consequently, learning could be regarded more as gap filling or enriching than as conceptual change (Chi, 2008). If we consider the proportion of correct conceptual models and the amount of progress in Studies I and II, this finding suggests that it is indeed beneficial to try to promote students' conceptual understanding of electric circuits as early as the elementary school level. At this early stage of science learning the students do not have deeply-rooted misconceptions because their ideas about the functioning of electrical circuits are not yet coherent and consistent. Once the students acquire more experiences with the electrical circuits, and their ideas become more coherent, their resistance to new ideas increases accordingly (e.g., McDermott & Shaffer 1992; Reiner et al., 2000).

5.3. Challenges for future studies

The present set of studies is one of the few attempts to explore the potential of combining laboratory and simulation activities in science education and the first empirical study that has been able to demonstrate unambiguously the effectiveness of the combination. Consequently, the study needs to be taken as an exploratory study calling for further replications with various extensions. The present studies were conducted in the domain of electricity and in the elementary school context. It remains to be seen whether further studies will yield similar results in different school levels and domains.

A future study could also investigate how different ways of combining simulation and laboratory activities affect the learning processes and outcomes. Present studies have emphasised the importance of using the simulation and the real circuits in parallel. The distinctive and innovative feature of the parallel combination is that each experiment is conducted with real *and* virtual equipment in a row. The rationale for the parallel combination is that when both representations are simultaneously available it is easier for the students to build cognitive links over the representations. However, Zacharia (2007) with his colleagues (Zacharia et al., 2008) has reported similar results, that is, results that favour combining simulation and laboratory activities with a sequential combination; laboratory activities in the first part of the intervention (no simulation) and simulation activities in the second part (no laboratory). This means, under the assumption that these results were truly caused by the combination (cf. sections 1.2.4. and 5.1.), that students benefited from the use of two different representations even without having the representations available at the same time. It still seems plausible that it would be easier to relate two synchronously available representations (parallel combination) than two asynchronously available representations (sequential combination) (cf. Ainsworth, 2006; Gentner et al., 2003; Kurtz et al., 2001).

Another issue worth exploring is the order of representations in the combination(s). In the present set of studies the decision to ask the students to construct each circuit first with the simulation was based on the assumption that constructing virtual circuits is easier than real circuits (cf. Finkelstein et al., 2005), and that the virtual circuit could then serve as a point of reference when the students reconstruct the circuit with the real equipment (cf. Ronen & Eliahu, 2000). However, assuming that the students could cope with the challenges that are related to learning with and from the real circuits (cf. McDermott & Shaffer), reversing this order could make it even easier for the students to relate the real and the virtual circuits; for instance, the students could adjust the battery in the simulation to correspond with the voltage of the real battery. These issues could be clarified in studies comparing various parallel and sequential combinations of simulation and laboratory activities in different school levels and domains.

Finally, a future study with a bigger sample should also investigate how different levels and types of instructional support affect students' learning performance in the combination learning environment. Results of Study II showed that explicit instruction, which provided more support and structure for the inquiry process than implicit instruction, was needed when the simulation was used on its own in order to promote students' conceptual understanding, but when the simulation and laboratory activities were combined, a less structured environment produced equally good learning outcomes than a structured environment, and in the less structured environment learning required less time from students. This finding suggests that the relationship between the instructional support and the learning environment might be more complex when simulation and laboratory activities are combined than when a simulation is used alone.

References

Ainsworth, S.E (2006) DeFT: A conceptual framework for learning with multiple representations. *Learning and Instruction*, 16, 183-198.

Ainsworth, S. (2008). The educational value of multiple representations when learning complex scientific concepts. In J. K. Gilbert & M. Reiner & M. Nakhlel (Eds.), *Visualization: Theory and Practice in Science Education* (pp. 191-208). New York: Springer.

Armstrong, A., & Casement, C. (1998). *The child and the machine: Why computers may put our children's education at risk.* Ontario: Key Porter Books.

Baki, A., Kosa, T. & Guven, B. (2009). A comparative study of the effects of using dynamic geometry software and physical manipulatives on the spatial visualisation skills of pre-service mathematics teachers. *British Journal of Educational Technology*, 42, 291–310.

Borges, A.T., & Gilbert, J.K. (1999). Mental models of electricity. *International Journal of Science Education*, 21(1), 95–117.

Bransford, J. D., Brown, A. L. & Cocking, R. R. (2000). *How people learn.* DC National Academy Press Washington.

Campbell, J. O., J. R. Bourne, P. Mosterman, and A. J. Brodersen. The Effectiveness of Learning Simulations for Electronic Laboratories. *Journal of Engineering Education,* 91, 81–87.

Chambers, S.K. & Andre, T. (1997). Gender, prior knowledge, interest, and experience in electricity and conceptual change text manipulations in learning about direct current. *Journal of Research in Science Teaching*, 34, 107-123.

Chang, K., Chen, Y., Lin, H. & Sung, Y. (2008). Effects of learning support in simulation-based physics learning. *Computers & Education*, 4, 1486-1498.

Chen, S. (2010). The view of scientific inquiry conveyed by simulation-based virtual laboratories. *Computers & Education*, 55, 1123–1130.

Chi, M.T.H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *Handbook of research on conceptual change* (pp. 61–82). Hillsdale, NJ: Erlbaum.

Chi, M. T. H. & VanLehn, K. A. (1991). The content of physics self-explanations. *Journal of the Learning Sciences*, 1, 69-105.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research*, *63*, 1-49.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed). NJ: Erlbaum.

Cohen, R., Eylon, B., & Ganiel, M. (1983). Potential difference and current in simple electric circuits: A study of students' concepts. *American Journal of Physics, 51,* 407–412.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika, 16(3)*, 297–334.

Electricity Exploration Tool. Adobe® Flash application. (2003). Brighton, UK: digitalbrain plc.

Finkelstein, N.D., Adams, W.K., Keller, C.J., Kohl, P.B., Perkins, K.K., Podolefsky, N.S., Reid, S. & LeMaster, R. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. Physical Review Special Topics—*Physics Education Research*, 1, 010103, 1–8.

Flick, L. (1993). The meanings of hands-on science. *Journal of Science Teacher Education*, 4, 1-8.

Flick, L. (2007). Reexamining 'hands-on science' as a tool for learning. *Science Education at the Crossroads*, Sept, 23–25.

Frederiksen, J.R., White, B.Y. & Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching*, 36, 806–836.

Fund Z. (2007) The effects of scaffolded computerized science problem-solving on achievement outcomes: a comparative study of support programs. *Journal of Computer Assisted Learning* 23, 410–424.

Gentner, D. & Gentner, D.R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A.L. Stevens (Eds.), *Mental models* (pp. 99–129). Hillsdale, NJ: Erlbaum.

Gentner, D. & Holyoak, K. J. (1997). Reasoning and learning by analogy: Introduction. *American Psychologist*, 52, 32–34.

Gentner, D., Loewenstein, J. & Hung, B. (2007). Comparison facilitates children's learning of names for parts. *Journal of Cognition and Development*, 8. 285-307.

Gentner, D., Loewenstein, J., Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, 95(2), 393–408.

Gentner, D. & Medina, J. (1998). Similarity and the development of rules. *Cognition,* 65, 263–297.

Gick, M. L. & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology,* 12, 306–355.

Gick, M. L. & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology,* 15, 1–38.

Goldstone, R.L. & Son, J.Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *The Journal of the Learning Sciences*, 14, 69–110.

Hart, C. (2008). Models in physics, models for physics learning, and why the distinction may matter in the case of electric circuits. *Research in Science Education*, 30, 529–544.

Hedges L.V. (1981) Distribution theory for Glass's estimator of effect sizes and related estimators. *Journal of Educational Statistics* 6, 107–128.

Hennessy S., Deaney R. & Ruthven K. (2006) Situated expertise in integrating use of multimedia simulation into secondary science teaching. *International Journal of Science Education,* 28, 701–732.

Hennessy, S. & O'Shea, T. (1993). Learner perceptions of realism and 'magic' in computer simulation. *British Journal of Educational Technology*, 24, 125–138.

Hofstein A. & Lunetta V. (2004) The laboratory in science education: foundations for the twenty-first century. *Science Education* 88, 24–54.

de Jong, T. (2006). Computer simulations: Technological advances in inquiry learning. *Science*, 312, 532–533.

de Jong, T., & van Joolingen, W.R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research*, 68(2), 179–201.

Kalyuga, S., Chandler, P. & Sweller, J. (1998). Levels of expertise and instructional design. *Human Factors,* 40, 1–17.

Kapur, M. (2008). Productive failure. *Cognition and Instruction*, 26, 379–424.

Kennedy, G. E. & Judd, T. S. (2007). Expectations and reality: Evaluating patterns of learning behaviour using audit trails. *Computers & Education*, 49(3), 840–855.

Klahr, D., Triona, L.M. & Williams, C. (2007). Hands on what? The relative effectiveness of physical vs. virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching*, 44, 183–203.

Kolloffel, B., Eysink, T. H. S., de Jong, T. & Wilhelm, P. (2009). The effects of representational format on learning combinatorics from an interactive computer-simulation. *Instructional Science,* 37, 503–517.

Kurtz, K. J., Miao, C. & Gentner, D. (2001). Learning by analogical bootstrapping. *Journal of the Learning Sciences*, 10, 417–446.

Kärrqvist C. (1985) The development of concepts by means of dialogues centred on experiments. In R. Duit, W. Jung & C. von Rhöneck (Eds.) *Aspects of Understanding Electricity* (pp. 215–226). Kiel: IPN.

Larkin, J. & Simon, H. (1987) Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science* 11, 69–100.

Lehtinen, E. & Rui, E. (1996). Computer supported complex learning: An environment for learning experimental methods and statistical inference. *Machine Mediated Learning*, 5, 149–175.

Limon, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal. *Learning and Instruction*, 11, 357–380.

Lou, Y., Abrami, P.C. & d'Apollonia, S. (2001). Small group and individual learning with technology: A meta-analysis. *Review of Educational Research*, 71, 449–521.

Marshall, J.A., & Young, E.S. (2006). Preservice Teachers' Theory Development in Physical and Simulated Environments. *Journal of Research in Science Teaching,* 43, 907–937.

Mayer, R. (2004). Should there be a three-strikes rule against pure discovery learning? *American Psychologist,* 59, 14–19.

McDermott L.C. & Shaffer P.S. (1992) Research as a guide for curriculum development: an example from introductory electricity. Part I: investigation of student understanding. *American Journal of Physics* 60, 994–1013.

Minner, D.D., Levy, A.J. & Century, J. (2010). Inquiry-based science instruction—What is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*, 47, 474–496.

Mosteller, F. & Bush, R. R. (1954). Selected quantitative techniques. In G. Lindzey (Ed.), *Handbook of social psychology: Volume 1 - Theory and method* (pp. 289–334). Reading, Mass.: Addison-Wesley.

National Science Teachers Association (NSTA). (2007). *NSTA position statement: The integral role of laboratory investigations in science instruction.* National Science Teachers Association.

Osborne R. (1983). Towards modifying children's ideas about electric current. *Research in Science and Technology Education* 1, 73–82.

Planinic, M., Boone, W.J., Krsnik, R. & Beilfuss, M. (2006). Exploring alternative conceptions from Newtonian dynamics and simple DC circuits: Links between item difficulty and item confidence. *Journal of Research in Science Teaching*, 43, 150–171.

Plötzner, R. (1995). The construction and coordination of complementary problem representations in physics. *Journal of Artificial Intelligence in Education*, 6, 203–238.

Rasch, T. & Schnotz, W. (2009). Interactive and non-interactive pictures in multimedia learning environments: Effects on learning outcomes and learning efficiency. *Learning and Instruction*, 19, 411–422.

Raven J.C. (1958) *Standard Progressive Matrices. Sets A, B, C, D and E.* H.K. Lewis & Co. Ltd., Cambridge, UK.

Reiner, M., Slotta, J.D., Chi, M.T.H. & Resnick, L.B. (2000). Naïve physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction*, 18, 1–34.

Ronen, M. & Eliahu, M. (2000). Simulation—A bridge between theory and reality: The case of electric circuits. *Journal of Computer Assisted Learning*, 16, 14–26.

Rosenthal, R. (1984). *Meta-analytic procedures for social research.* Beverly Hills, CA: Sage.

von Rhöneck C. & Grob K. (1990). Psychological aspects of learning about basic electricity. In H. Mandl, E. De Corte, N. Bennett & H.F. Friedrich (Eds.) *Learning and Instruction. European Research in an International Context*, Vol. 2.2. (pp. 589–603). UK: Pergamon.

Schmidt, R. A. & Bjork, R. A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science*, 3, 207–217.

Schwartz, D. (1995). The emergence of abstract representations in dyad problem solving. *Journal of the Learning Sciences*, 4, 321–354.

Sencar, S. & Eryılmaz, A. (2004). Factors mediating the effect of gender on ninth-grade Turkish students' misconceptions concerning electric circuits. *Journal of Research in Science Teaching*, 41, 603–616.

Shepardson, D.P. & Moje, E.B. (1999). The role of anomalous data in restructuring fourth graders' frameworks for understanding electric circuits. *International Journal of Science Education*, 21, 77–94.

Shipstone, D.M.(1984). A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education,* 6, 185–198.

Simon, H. (2000). Observations on the sciences of science learning. *Journal of Applied Developmental Psychology*, 21, 115–121.

Smith, G., Gnesdilow, D. & Puntambekar, S. (2010). Examining the combination of physical and virtual experiments in an inquiry science classroom. In C.Z. Zacharia, C.P. Constantinou & M. Papaevripidou (Eds.) *Proceedings of Computer Based Learning in Science (CBLIS) conference: application of new technologies in science and education* (pp. 153–163) Warsaw: OEIiZK.

Srinivasan S., Perez L.C., Palmer R.D., Brooks D.W., Wilson K. & Fowler D. (2006). Reality versus simulation. *Journal of Science Education and Technology* 15, 137–141.

Steinberg R.N. (2000). Computers in teaching science: to simulate or not to simulate? *American Journal of Physics* 68, 37–41.

Strike, K. A. & Posner, G. J. (1982). Conceptual change and science teaching. *European Journal of Science Education*, 4, 231-240.

Tabachnek-Schijf, H.J.M. & Simon, H.A. (1998). One Person, Multiple Representations: An Analyses of a Simple, Realistic Multiple Representation Learning Task. In M.W. van Someren, P. Reimann, H.P. Boshuizen & T. de Jong (Eds.), *Learning with Multiple Representations*, (pp. 197–236). Amsterdam: Pergamon, Elsevier Science Ltd.

Tao, P. & Gunstone, R. (1999). The process of conceptual change in force and motion during computer-supported physics instruction. *Journal of Research in Science Teaching*, 36, 859–882.

Taylor, R. & Chi, M.T.H. (2006). Simulation versus text: Acquisition of implicit and explicit information. *Journal of Educational Computing Research,* 35, 289–313.

Thompson, L., Gentner, D. & Loewenstein, J. (2000). Avoiding missed opportunities in managerial life: Analogical training more powerful than individual case training. *Organizational Behavior & Human Decision Process*, *82*, 60–75.

Triona L.M. & Klahr D. (2003) Point and click or grab and heft: comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction,* 21, 149–173.

Veermans, K., de Jong, T. & van Joolingen, W.R. (2006). Using heuristics to facilitate discovery learning in a simulation learning environment for a physics domain. *International Journal of Science Education*, 28, 341–361.

Vosniadou, S. (2002). On the nature of naive physics. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 61–76). Dordrecht: Kluwer.

Wallen, N.E. & Fraenkel, J.R. (2001). *Educational research: A guide to the process* (2nd ed.) NJ: Erlbaum.

Wieman, C.E., Adams, W.K. & Perkins, K.K. (2008). PhET: Simulations that enhance learning. *Science*, 322, 682–683.

Winn, W., Stahr, F., Sarason, C., Fruland, R., Oppenheimer, P. & Lee, Y-L. (2006). Learning oceanography from a computer simulation compared with direct experience at sea. *Journal of Research in Science Teaching*, 43, 25–42.

Wiser, M. & Amin, T. G. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction*, 11, 331–355.

Yuan, Y., Lee C.-Y. & Wang, C.-H. (2010). A comparison study of polyominoes explorations in a physical and virtual manipulative environment. *Journal of Computer Assisted Learning,* 26, 307–316.

Zacharia, Z.C. (2007). Comparing and combining real and virtual experimentation: An effort to enhance students' conceptual understanding of electric circuits. *Journal of Computer Assisted Learning*, 23, 120–132.

Zacharia, Z.C. & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction*, 21, 317–331.

Zacharia, Z.C., Olympiou, G. & Papaevripidou, M. (2008). Effects of experimenting with physical and virtual manipulatives on students' conceptual understanding in heat and temperature. *Journal of Research in Science Teaching*, 45, 1021–1035.