Chapter 17
The Impact of Virtual Laboratory Environments in Teaching-by-Inquiry Electric Circuits in Greek Secondary Education: The ElectroLab Project

Athanasios Taramopoulos and Dimitrios Psillos

Introduction

Virtual Laboratory Environments

The last two decades have seen the development of a large group of educational software in physical sciences, the virtual laboratory environments that simulate in a visual and functional manner the laboratories of physical sciences on a computer screen. This has been possible by exploiting modern multimedia technology, interactive interfaces, and direct and realistic handling of objects and parameters (Psillos et al., 2008). The ability of this software to be used in teaching in an analogous way to real school laboratories has initiated a discussion of redefinition of the role of the experiment in scientific teaching (Hofstein & Lunetta, 2004). A significant number of studies have shown that virtual laboratories as educational environments are not inferior to their real counterparts (Rutten, van Joolingen, & van der Veen, 2012). But virtual laboratory environments differ from one another in the affordances offered to the users (e.g., graphical presentations, microscopic phenomena views, degree of interaction with the simulated phenomena, etc.), in the fidelity of the represented physical world (from realistic to purely schematic representation, as shown in Fig. 17.1), the physical phenomena simulated, and the accuracy of the simulation. It has been found that these characteristics of the virtual laboratories may have a significant impact on the teaching outcome (Olympiou, Zacharia, & de Jong, 2012; Rutten et al., 2012).

A. Taramopoulos (✉)
General Lyceum of Nea Zichni Serron, Nea Zichni, Greece
e-mail: ttar@sch.gr

D. Psillos
Faculty of Education, Aristotle University of Thessaloniki, Thessaloniki, Greece
e-mail: psillos@eled.auth.gr

T. A. Mikropoulos (ed.), *Research on e-Learning and ICT in Education*,
https://doi.org/10.1007/978-3-319-95059-4_17

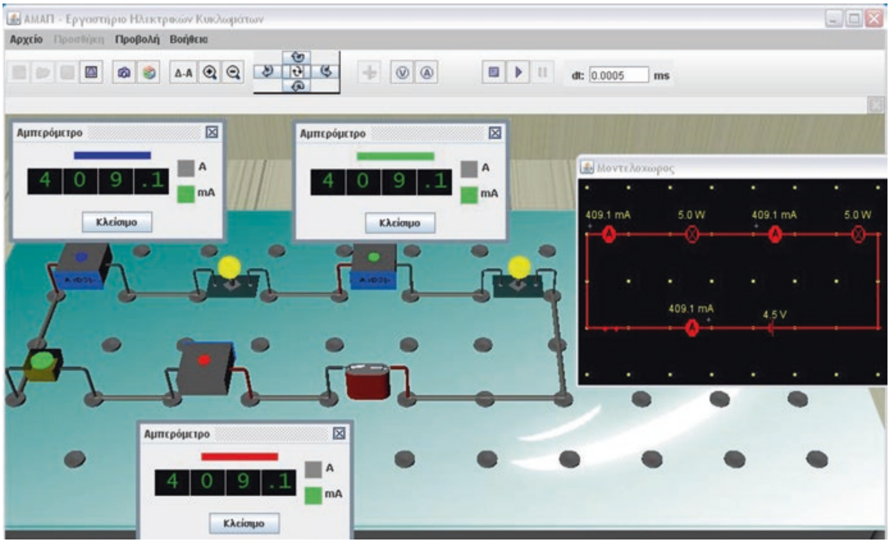


Fig. 17.1 The virtual laboratory of electric circuits of OLLE allows for the use of virtual instruments with different representation concreteness

Evaggelou and Kotsis remark in their review (2009) that such studies focus mainly on university students and only a few were tried out with elementary or secondary education students. Regarding secondary education, no study deals with the field of electric circuits, which is particularly suited to a comparison between virtual and real laboratory environments.

Teaching with Multiple Representations

One of the key features of virtual laboratory environments is the capacity to use multiple representations to present the simulated phenomena. Multimedia and multi-representational learning environments are widely used in classrooms and support a variety of learning activities. However, different types of representations differ in their computational effectiveness (Schnotz & Bannert, 2003), and the representations used in learning environments influence students' construction of scientific understanding and their ability to transfer scientific knowledge to various situations (Scheiter, Gerjets, Huk, Imhof, & Kammerer, 2009). There is evidence that utilizing multi-representational learning environments helps foster students' problem-solving ability, since they are less prone to be confused by the representation in which the problem is manifested (Rosengrant, Etkina, & Van Heuvelen, 2006). However, little is still known about how we learn from different representational formats and how these processes are related to learning outcomes (Kühl, Scheiter, Gerjets, & Gemballa, 2011).

Nevertheless it is generally believed that students may gain from the properties of each representation used and that multi-representational instruction will lead to a deeper understanding of the scientific domain under study. Such a deeper understanding of the domain may also occur when students build abstractions by translating between representations in a multi-representational environment (Ainsworth & van Labeke, 2004). However the issue is not settled yet. Learning with multiple representations presents various difficulties for the students, since for each representation used they have to understand the form of the representation, the relation between the representation and the domain, how to select the most appropriate representation to use when confronted with a problem, and how to construct an appropriate representation (Ainsworth, 2006). Furthermore, different representations require students to correlate different sources of information, which may cause them to display a split-attention effect (Mayer & Moreno, 1998), also producing a heavy cognitive load and leaving few resources available for actual learning (Sweller, van Merrienboer, & Paas, 1998).

Rationale

In the field of DC electric circuits, in particular, which is a field of physical sciences that everyone encounters daily and has been a topic of science education continuously over the last 30 years, it has been found that important and widely spread alternative views exist which are very hard to change (Engelhardt & Beichner, 2004; Psillos, 1997). Consequently, studies with virtual or physical laboratory environments have mainly focused on the students' conceptual difficulties, overlooking other learning objectives, like the ability to transfer knowledge from the teaching environment to the real world for solving everyday problems or student understanding of how to design and implement experiments with electric circuits. Besides, to the best of our knowledge, there exist no studies comparing the effectiveness of teaching DC electric circuits in secondary education using investigative activities employing virtual laboratories that contain object representations of various levels of concreteness. Such studies might contribute significantly to our understanding of the differences reported in students' problem-solving abilities and shed light on the difficulties they encounter in translating a circuit from one form to another. Circuit transformation and knowledge transfer from one representation to another are essential ingredients for problem solving and experimentation, as circuit schematics are usually presented or drawn in the design phase whereas real or virtual circuits are realized in the implementation phase.

In this framework, the ElectroLab project was designed and is being implemented by researchers and experienced teachers. The project is a research and development program aiming at developing a suitable educational virtual laboratory environment and multiply assessing the role that virtual laboratory environments may play when incorporated in teaching-by-inquiry DC electric circuits (Psillos et al., 2008). The program is implemented through field research studies in students of secondary education in Greece, comparing various aspects of teaching effectiveness when it is performed with virtual laboratory environments of various features.

In the ElectroLab project, a comparison of the impact of virtual laboratories is made when used in teaching by inquiry DC electric circuits with regard to (1) the conceptual evolution of students, (2) the students' ability to transfer knowledge to other representations by transforming an electric circuit from one representation to another (real, virtual, schematic), and (3) the students' ability to design and carry out experiments with simple electric circuits. In this chapter results of this program are reviewed along the three aforementioned axes and are compared to similar international research studies.

The OLLE Virtual Laboratory Environment

Most of the ElectroLab studies used the virtual laboratory of electric circuits of the Open Learning Laboratory Environment (OLLE). OLLE is an open three-dimensional virtual laboratory in the fields of optics and electricity with navigation and rotation capabilities (Bisdikian, Psillos, Hatzikraniotis, & Barbas, 2006; Psillos et al., 2008; Taramopoulos & Psillos, 2017; Taramopoulos, Psillos, & Hatzikraniotis, 2011b). Users may construct the setup of their choice, adjust the parameters of their instruments, and explore their behavior while the virtual instruments are fully and continuously functional. It was developed in the general framework of our research and development program, and it is widely used in Greece and other Greek-speaking countries either in optics or in electricity (Olympiou et al., 2012; Taramopoulos & Psillos, 2017).

OLLE also provides its users with an additional tool in the virtual laboratory, which bridges the gap between the realistic virtual laboratory world and the governing underlying physics laws: the model space tool (Fig. 17.1), which depicts a two-dimensional symbolic representation of the real laboratory setup. In optics the model space tool depicts in real time the light rays and models of the lenses and the other instruments used; in static electricity and magnetism, the model space tool shows synchronously the symbols of the electric charges and magnets and the accompanying electric and magnetic fields of the user's virtual setup; and in the electric circuits laboratory, it displays in real time the schematics of the circuit constructed by the user. The model space is more realistic and concrete than abstract general laws, but also more abstract and general than a depiction of the physical phenomena. The model space is thus positioned between physical phenomena and physical laws and may be considered to be a model of the laboratory setup. This duality of representation designed into OLLE is hoped to be capable of effectively scaffolding learners to acquire a deeper level of understanding and overcome higher-level difficulties in the domain of electricity and optics.

OLLE allows its user to store the experimental setup in the form of a fully functional Java applet. In practical terms, this means that from each experimental setup, a new simulation can be exported, in the form of an applet, which can be executed independently of OLLE. These simulations are similar in appearance to the two-dimensional model space tool, with the addition of the freedom of handling existing in the three-dimensional virtual lab (ability to move an object and alter its properties). These virtual labs with abstract representations of their objects are therefore fully functional two-dimensional symbolic multi-parametric representations of the virtual laboratory, highly consistent with the theory.

OLLE thus provides the teacher with three distinct possibilities for use: a realistic three-dimensional virtual laboratory, a fully functional abstract two-dimensional model (applet), and a virtual laboratory where the concrete and abstract representations coexist side by side and are dynamically linked. It is up to the teacher to use any of these possibilities, depending on the desired learning outcomes in each case. This unique design feature makes OLLE especially suitable for our program.

Characteristics of the Teaching Interventions

Involving students in laboratory activities in science courses is alleged to contribute not only to the construction of content knowledge but also to understanding aspects of scientific inquiry. Physics teaching is compulsory in Greek secondary education and so is the curriculum. In our studies, an innovative guided-inquiry approach was adopted with some variations depending on the level and specific case objectives. The main features are that students, guided by the teacher and suitably structured worksheets, investigate the behavior of electric circuits and the laws they adhere to. All materials were adapted to the junior or senior high school curriculum, depending on the age of the students. The various interventions were based on coherent teaching/learning sequences consisting of structured activity worksheets based on a laboratory variation of the predict-observe-explain strategy (White & Gunstone, 1992) with activities concerning setting of problems and questions, making predictions, designing and performing suitable experiments, discussions, interpretation of results, drawing, and sharing conclusions. Students were guided through a sequence of phases to explore a problem (e.g., construct an appropriate circuit, and measure the intensity of the current with different bulbs), search for the answer, design experiments, take data, cooperate, discuss, evaluate their predictions, and present their findings. Guidance during teaching varied. It was lessened as the teaching sequence progressed and students became more familiar with scientific experimental procedures. Teaching can thus be classified as starting with structured inquiry in the first units and gradually shifting and ending in guided inquiry in the last units (Zion & Shedletzky, 2006).

Work in class took place in groups of two, whereas the activity worksheets were separately completed by each student. Most of the worksheets of the teaching sequences were of hourly duration, and there were a lot of activities in the worksheets where students discuss in class and take notes. This was deemed necessary to stimulate students' exchange of views and ideas, help student reflect on their views, and restructure their knowledge. At the end of each worksheet, students were assigned homework comprised of meta-cognitive questions. Homework was done individually.

Impact on Students' Conceptual Evolution

In the area of DC electric circuits, research has shown that students carry intuitive conceptions acquired from their everyday experience, which are usually considerably different from the scientifically accepted views and are resistant to change (Engelhardt & Beichner, 2004; McDermott & Shaffer, 1992; Psillos, 1997). Unlike a physical laboratory, in a virtual one the circuit elements do not have a fixed representation and may be presented with a representation fidelity anywhere between highly realistic (concrete representation) to purely schematic (abstract representation), which may influence learning outcomes. It has been found that traditional teaching using abstract electric circuit representations leads to an increased ability to solve simple problems or problems similar to the ones dealt with during teaching, compared to teaching using realistic representations of circuit elements (Moreno, Reisslein, & Ozogul, 2009). It is suggested that the absence of excessive information in the representation helps students focus on the important aspects of the phenomena under study (Reisslein, Moreno, & Ozogul, 2010). The same researchers have also found that the combination of using abstract circuit schematics with a realistic everyday description of a problem leads to increased problem-solving ability on the part of students, compared to purely abstract or purely realistic approaches. Increased problem-solving ability in electric circuits is also reported when students are taught using simultaneously abstract and realistic circuit representations, which effectively supports bridging and blending newly acquired and pre-existing knowledge (Moreno, Ozogul, & Reisslein, 2011).

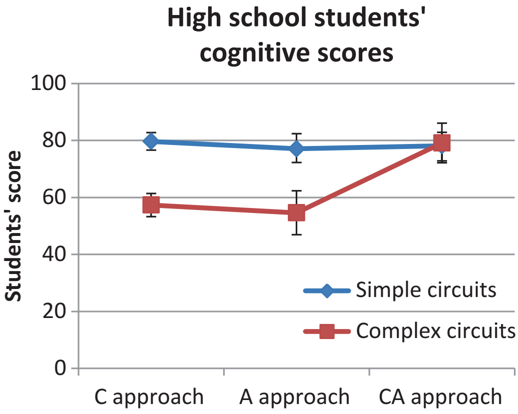
On the other hand, studies in electric circuits and other fields which focus on shifting the representation used during teaching from concrete representations to abstract ones or vice versa report various results. Some researchers suggest that student performance is improved by shifting from concrete to abstract representations (Goldstone & Son, 2005; McNeil & Fyfe, 2012), while others that the shift of representations used during teaching should be from abstract to concrete (Johnson, Reisslein, & Reisslein, 2013). Despite this disagreement, all these results provide some evidence that utilizing multi-representational learning environments may foster students' problem-solving ability or increase their understanding of scientific content. Such a result may be attributed to students being less prone to be confused by the representation in which a problem is displayed, that students gain from the properties of each representation used, and that multi-representational instruction may lead to the construction of a higher-quality mental model and a deeper understanding of the domain under study (de Jong et al., 1998; Seufert, 2003).

However, the above studies were not conducted with a teaching-by-inquiry intervention utilizing open virtual laboratory environments but used either static images or interactive multimedia software with embedded computer-based instruction and drills. Therefore the students did not have the ability to interactively use multiple representations and freely switch between representations at any time instead of representation shifting midway through the teaching intervention. Such an inquiry-based teaching study with virtual laboratory environments was carried out by Jaakkola and Veermans (2015), who conducted their research in primary school. These researchers concluded that pupils benefit more from constantly using a certain representation instead of using multiple representations. They also concluded that the effects of concrete and abstract representations in science education are notably different in elementary school as compared to college contexts, where studies indicate that students benefit more from using multiple representations during teaching instead of being restricted to a single representation (Olympiou et al., 2012).

The impact of virtual laboratories on the students' conceptual evolution in comparison with the impact of hands-on school laboratories when both environments are similarly used in teaching-by-inquiry electric circuits in students of the third grade of junior high school in Greece was studied by Taramopoulos et al. (2011b). The results of this study indicate that the use of virtual or real laboratories does not seem to affect the conceptual evolution of students in electric circuits, since in both cases similar improvements are observed, in agreement with similar international studies (Jaakkola, Nurmi, & Lehtinen, 2011; Zacharia & Olympiou, 2011). Whenever there are reports of differences in the conceptual evolution outcomes, these are attributed to additional characteristics of the virtual laboratories. In particular, Finkelstein et al. (2005) report that the affordance of observing moving charges along electric circuit conductors may scaffold the understanding of related phenomena, and teaching with virtual laboratories that offer such affordances may lead to significantly increased conceptual evolution of students compared to teaching using real laboratories, which does not allow students to view microscopic phenomena.

In one study, Taramopoulos et al. (2011b), exploring the impact of the fidelity of the representation of the real world, report that, for junior high school students, the use of virtual laboratory environments with realistic concrete representations leads to similar conceptual improvement to the use of virtual laboratories with schematics of electric circuits. This is in line with international reports that a circuit in the form of a functional schematic representation when utilized in investigative activities may be an effective tool and facilitate the enhancement of students' conceptual evolution (Wieman, Adams, & Perkins, 2008). But when the virtual laboratory environment combines realistically represented instruments with dynamically linked schematics so that any change in one representation is automatically shown in the other, senior high school students who used the dynamically linked representations environment outperform students who used only a single representation when dealing with problems of relatively high complexity, whereas their scores are similar when involved only with relatively simple problems in electric circuits (Taramopoulos & Psillos, 2017). Figure 17.2 shows graphically the students' scores after the teaching intervention in a posttest cognitive test. It is clear that the students of the CA approach, in which realistic and abstract representations dynamically linked to each other were used, outperform the other two groups (C approach which used concrete

Fig. 17.2 Students' posttest scores for cognitive test with simple and complex problems for teaching-by-inquiry electric circuits with concrete objects (C approach), abstract objects (A approach), and dynamically linked concrete and abstract objects (CA approach)



representations and A group which used abstract representations) when the students face complex problems in electric circuits (red line) but have similar scores to the other two groups when confronted with simple problems (blue line). In fact, students in the CA approach seem to have similar posttest scores for both simple and complex problems, and thus their scores seem to be unaffected by the complexity of the problem. This might indicate that these students have reached a deeper understanding of the subject than the other two groups, so that problems which seem complex to the students of the C or the A approach are easier to comprehend and thus are simple to them.

These results are in line with international research studies in electric circuits in university students according to which different representations may lead to different cognitive results in electric circuits (Moreno et al., 2009) and in other fields of physical sciences (Olympiou et al., 2012). Taking into account all studies, it is suggested that in electric circuits it may be advantageous for a virtual laboratory environment to use constantly only one particular representation when utilized in elementary education (Jaakkola & Veermans, 2015) and dynamically linked realistic and schematic representations when utilized in secondary education (Taramopoulos & Psillos, 2017) or with older students (Olympiou et al., 2012), as at these ages students are more accustomed to using scientific models, and the use of dynamically linked multiple representations may help them build bridges between the models and real objects and detach from a specific representation (Goldstone & Son, 2005; Taramopoulos, 2012).

Impact on Transforming Electric Circuits

Ainsworth (2006) suggests that if multiple representations aim at constraining interpretation or constructing deeper understanding, then translating across these representations should be either automated or scaffolded. In electric circuits a student may be required to first study the circuit's schematics, analyze the circuit's behavior, and then construct it in a virtual or real environment. A student may therefore be frequently required to translate between forms and representations of circuits, which has been found to pose difficulties (Kozma, 2003). However, students often fail to comprehend the relation between two forms or representations, and this may even inhibit learning (Ainsworth, Bibby, & Wood, 2002). In an attempt to better support learning, many learning environments, such as OLLE, have incorporated automatic translation, in which the effects of a student's actions on one form are synchronously shown on another (dynamically linked representations). This is hoped to lessen the burden of performing representation translations on the students, reducing their cognitive load (Scaife & Rogers, 1996), and at the same time support bridging between the representations (Kozma, Russell, Jones, Marx, & Davis, 1996). On the other hand, such an automation may leave students as passive attendees and prevent them from constructing the required understanding (Ainsworth, 1999). To avoid this, the students need to be explicitly guided to study the relationships between the various representations as they unfold before them via properly structured activities and worksheets. Such studies of the ability to transform circuits from one form to another when high school students are actively involved in investigative activities in open virtual laboratory environments have not been performed internationally (Rutten et al., 2012).

Studying the ability of junior high school students to transform a given circuit from one form to another (real, realistic virtual, or schematic), Taramopoulos and Psillos report that the results depend on the complexity of the circuit: for simple circuits the students transform the circuit successfully regardless of the features of the virtual laboratory they used during teaching, but for more complex circuits, the students who used virtual laboratories with dynamically linked realistic and schematic representations during teaching seem to outperform the rest (Taramopoulos, 2012; Taramopoulos & Psillos, 2014). The results of these studies with groups of students who used concrete virtual objects (C approach) and students who used dynamically linked concrete and abstract virtual objects (CA approach) show that the students of both groups seem to be able to transform simple circuits excellently regardless of the direction of transformation (concrete to abstract or vice versa), but all students seem to be less effective in transforming complex circuits, with students of the CA approach outperforming the students of the C approach.

Impact on Experiment Design and Implementation

The ability to design experiments is considered to be one of the most important skills linked to laboratory investigations, possibly surpassing in importance even the actual execution of the experiment, as it is related not only to the content under study but to scientific methodology as well (Garratt & Tomlinson, 2001; Johnstone & Al-Shuaili, 2001). In designing experiments students are involved in identifying variables; listing the devices and instruments needed; describing the experimental setup, the phenomena taking place, and the experimental process; taking and analyzing measurements; and evaluating results. Virtual laboratory environments provide a powerful tool for investigative activities, since students can design aspects of an experiment using multimedia facilities, easily manipulate objects, and try out investigations. Recent studies suggest that virtual laboratories provide affordances which can support students' engagement in experimental investigative activities and enhance their understanding of aspects of scientific inquiry (Klahr, Triona, & Williams, 2007; Lefkos, Psillos, & Hatzikraniotis, 2011).

However, the potential of virtual laboratories to support the development of experimental skills in students in electric circuits has not yet been fully explored (Rutten et al., 2012). Besides, it still remains an open issue whether the representation used in the virtual lab utilized during teaching will have an effect on the students' ability to design and perform experiments. Taramopoulos, Psillos, and Hatzikraniotis (2011a) report that most students who have used virtual laboratories during teaching are able to successfully design and implement an experimental process with simple electric circuits after a teaching intervention where experimental design is not taught directly but indirectly through the continuous involvement of students with electric circuit experiments. Students seem to be able to form hypotheses to answer given research questions, to recognize the variables which affect the phenomenon under consideration, to find the instruments which need to be used for their experimental setup, to design the schematics of suitable circuits to explore the problem, to describe the experimental procedure which need to be followed, to construct the circuit of their experiment, and to record the necessary data, analyze them, calculate the final results, and evaluate them. This is performed successfully regardless of the representation used in the virtual lab utilized during teaching, whether this is realistic, schematic, or dynamically linked realistic and schematic (Taramopoulos, 2012).

Conclusions

The results of our ongoing research and development program, the ElectroLab project, show that teaching-by-inquiry electric circuits using virtual laboratory environments seem to be adequately supporting the conceptual evolution of students (Finkelstein et al., 2005; Jaakkola & Veermans, 2015; Taramopoulos & Psillos, 2014, 2017; Taramopoulos et al., 2011b), the development of skills to transform electric circuits from one form to another (Finkelstein et al., 2005; Goldstone & Son, 2005; Taramopoulos, 2012), and the development of experimental design and implementation skills with simple electric circuits (Taramopoulos, 2012; Taramopoulos et al., 2011a). Contributing factors seem to be specific design features of the virtual laboratories such as the existence of real-time synchronous graphical representations or the existence of dynamically linked representations of different levels of concreteness (realistic and abstract). Such affordances may act as scaffolds for students to acquire a deeper understanding of the domain of electric circuits and consequently be able to successfully cope with problems or circuits of higher complexity. Therefore, virtual laboratories offer teachers an environment into which they can design, develop, and implement investigative laboratory activities, making students interact in a natural way with virtual instruments and actively explore physical phenomena, thus acquiring a deeper understanding that may be transferred to other similar conditions while at the same time developing experimental skills.

References

Ainsworth, S. (1999). The functions of multiple representations. *Computers and Education, 33*, 131–152.

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

Ainsworth, S., Bibby, P., & Wood, D. (2002). Examining the effects of different multiple representational systems in learning primary mathematics. *Journal of the Learning Sciences, 11*(1), 25–61.

Ainsworth, S., & van Labeke, N. (2004). Multiple forms of dynamic representation. *Learning and Instruction, 14*, 241–255.

Bisdikian, G., Psillos, D., Hatzikraniotis, E., & Barbas, A. (2006). An open laboratory and learning environment (OLLE) in optics. In V. Dagdilelis & D. Psillos (Eds.), *Proceedings of the 5th Panhellenic Conference of ICT in Education* (pp. 188–195). Thessaloniki, Greece (in Greek).

de Jong, T., Ainsworth, S., Dobson, M., van der Hulst, A., Levonen, J., Reimann, P., et al. (1998). Acquiring knowledge in science and mathematics: The use of multiple representations in technology based learning environments. In M. van Someren, P. Reimann, H. Boshuizen, & T. de Jong (Eds.), *Learning with multiple representations* (pp. 9–41). Oxford: Elsevier Science.

Engelhardt, P. V., & Beichner, R. J. (2004). Students' understanding of direct current resistive electrical circuits. *American Journal of Physics, 72*(1), 98–115.

Evaggelou, F., & Kotsis, K. (2009). Characteristics of studies in international bibliography regarding learning outcomes from the comparison of virtual and real experiments in teaching and learning of physics. In P. Kariotoglou, A. Spirtou, & A. Zoupidis (Eds.), *Proceedings of the 6th Panhellenic Conference of the Union for Education in Physical Sciences and Technology* (pp. 335–342) (in Greek).

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., et al. (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*, 1–8.

Garratt, J., & Tomlinson, J. (2001). Experimental design – Can it be learned? *University Chemistry Education, 5*(2), 74–79.

Goldstone, R. L., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *The Journal of the Learning Sciences, 14*(1), 69–110.

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*, 28–54.

Jaakkola, T., Nurmi, S., & Lehtinen, E. (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.

Jaakkola, T., & Veermans, K. (2015). Effects of abstract and concrete simulation elements on science learning. *Journal of Computer Assisted Learning, 31*, 300–313.

Johnson, A. M., Reisslein, J., & Reisslein, M. (2013). Representation sequencing in computer-based engineering education. *Computers & Education, 72*, 249–261. https://doi.org/10.1016/j.compedu.2013.11.010
Johnstone, A. H., & Al-Shuaili, A. (2001). Learning in the laboratory; some thoughts from the literature. *University Chemistry Education, 5*(1), 42–51.
Klahr, D., Triona, L., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching, 44*(1), 183.
Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction, 13*, 205–226.
Kozma, R. B., Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple, linked representations to facilitate science understanding. In S. Vosniadou, R. Glaser, E. DeCorte, & H. Mandel (Eds.), *International perspectives on the psychological foundations of technology-based learning environments* (pp. 41–60). Hillsdale, NJ: Erlbaum.
Kühl, T., Scheiter, T., Gerjets, P., & Gemballa, S. (2011). Can differences in learning strategies explain the benefits of learning from static and dynamic visualizations? *Computers & Education, 56*, 176–187.
Lefkos, I., Psillos, D., & Hatzikraniotis, E. (2011). Designing experiments on thermal interactions by secondary students in a simulated laboratory environment. *Research in Science and Technological Education, 29*(2), 189–204.
Mayer, R. E., & Moreno, R. (1998). A split-attention effect in multimedia learning: Evidence for dual processing systems in working memory. *Journal of Educational Psychology, 90*, 312–320.
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*(11), 994–1003.
McNeil, N. M., & Fyfe, E. R. (2012). "Concreteness fading" promotes transfer of mathematical knowledge. *Learning and Instruction, 22*, 440–448.
Moreno, R., Ozogul, G., & Reisslein, M. (2011). Teaching with concrete and abstract visual representations: Effects on students' problem solving, problem representations, and learning perceptions. *Journal of Educational Psycology, 103*(1), 32–47.
Moreno, R., Reisslein, M., & Ozogul, G. (2009). Pre-College Electrical Engineering Instruction: Do abstract or contextualized representations promote better learning? In *Proceedings of the IEEE/ASEE Frontiers in Education Conference*, San Antonio, Texas, session M4J (pp. 1–6).
Olympiou, G., Zacharia, Z., & de Jong, T. (2012). Making the invisible visible: Enhancing students' conceptual understanding by introducing representations of abstract objects in a simulation. *Instructional Science, 41*(3), 575–596. https://doi.org/10.1007/s11251-012-9245-2
Psillos, D. (1997). Teaching electricity (invited paper). In A. Tiberghien, E. L. Jossem, & J. Barojas (Eds.), *Connecting research in physics education with teacher education*. International Commission on Physics Education, 1997–1998.
Psillos, D., Taramopoulos, A., Hatzikraniotis, E., Barbas, A., Molohidis, A., & Bisdikian, G. (2008). An open laboratory learning environment (OLLE) in the field of electricity. In H. Aggeli & N. Valanidis (Eds.), *Proceedings of the 6th Panhellenic Conference of the Greek Association for ICT in Education*, Cyprus (pp. 384–391) (in Greek).
Reisslein, M., Moreno, R., & Ozogul, G. (2010). Pre-College Electrical Engineering Instruction: The impact of abstract vs. contextualized representation and practice on learning. *Journal of Engineering Education, 99*, 225–235.
Rosengrant, D., Etkina, E., & Van Heuvelen, A. (2006). An overview of recent research on multiple representations. In L. McCullough, P. Heron, & L. Hsu (Eds.), *Physics Education Research Conference, AIP Conference Proceedings* (pp. 149–152).
Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers and Education, 58*, 136–153.
Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies, 45*(2), 185–213.

Scheiter, K., Gerjets, P., Huk, T., Imhof, B., & Kammerer, Y. (2009). The effects of realism in learning with dynamic visualizations. *Learning and Instruction, 19*, 481–494.

Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representations. *Learning and Instruction, 13*(2), 141–156.

Seufert, T. (2003). Supporting coherence formation in learning from multiple representations. *Learning and Instruction, 13*, 227–237.

Sweller, J., van Merrienboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*, 251–296.

Taramopoulos, A. (2012). *Investigating the effectiveness of simulated virtual laboratory environments in teaching Physics in compulsory education*. PhD. thesis, Aristotle University of Thessaloniki, Thessaloniki.

Taramopoulos, A., & Psillos, D. (2014). Raising the level of understanding through the use of dynamically linked concrete and abstract representations in virtual laboratory environments in electric circuits. In C. P. Constantinou, N. Papadouris, & A. Hadjigeorgiou (Eds.), *E-Book Proceedings of the ESERA 2013 Conference*, Nicosia, Cyprus (pp. 157–163). ISBN: 978-9963-700-77-6.

Taramopoulos, A., & Psillos, D. (2017). Complex phenomena understanding in electricity through dynamically linked concrete and abstract representations. *Journal of Computer Assisted Learning, 33*(2), 151–163. https://doi.org/10.1111/jcal.12174

Taramopoulos, A., Psillos, D., & Hatzikraniotis, E. (2011a). Designing virtual experiments in electric circuits by high school students. In *9th International ESERA Conference*, Lyon, France.

Taramopoulos, A., Psillos, D., & Hatzikraniotis, E. (2011b). Teaching by inquiry electric circuits in virtual and real laboratory environments. In A. Jimoyiannis (Ed.), *Research on e-learning and ICT in education: Technological, pedagogical and instructional issues* (ch. 16, pp. 209–222). New York: Springer.

White, R., & Gunstone, R. (1992). *Probing understanding*. London: Palmer Press.

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

Zacharia, Z. C., & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction, 21*(3), 317–331.

Zion, M., & Shedletzky, E. (2006). Overcoming the challenge of teaching open inquiry. *The Science Education Review, 5*(1), 8–10.