Conceptual understanding of electrical circuits in secondary vocational engineering education: Combining traditional instruction with inquiry learning in a virtual lab

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Abstract

Background

Traditionally, engineering curricula about electrical circuits use textbook instruction and hands-on lessons, which are effective approaches for teaching students terms and definitions, the procedural use of formulas, and how to build circuits. However, students often lack conceptual understanding.

Purpose (Hypothesis)

The aim of this study was to find out how the acquisition of conceptual understanding can be facilitated. It was hypothesized that adding an extra instructional approach in the form of inquiry learning in a virtual lab would be more effective than relying on traditional instruction alone.

Design/Method

Students from secondary vocational engineering education were randomly assigned to one of two conditions in a quasi-experimental study. In the traditional condition the traditional curriculum was supplemented with additional (computer-based) practice. In the virtual lab condition the traditional curriculum was supplemented with inquiry learning in a virtual lab.

Results

The results showed that students in the virtual lab condition scored significantly higher on conceptual understanding (Cohen's *d* = 0.65) *and* on procedural skills (*d* = 0.76). In particular, students in this condition scored higher on solving complex problems (*d* = 1.19). This was true for both complex conceptual and complex procedural problems.

Conclusion

The observation that students in the virtual lab condition not only acquired better conceptual understanding but also developed better procedural skills than students in the traditional condition gives support for the idea that conceptual understanding and procedural skills develop in an iterative fashion.

Keywords

Inquiry learning, virtual labs, conceptual understanding

Introduction

The concept of electricity is abstract and hard to grasp. Electricity is invisible yet omnipresent in our lives. Many models of and analogies for electricity have been used, but none of them fully explains all of its aspects (Frederiksen, White, & Gutwill, 1999; Hart, 2008). Electricity's intangible nature causes many students, even those who have completed a physics course, to have incorrect ideas about it and about the behavior of electrical circuits.

McDermott (1991) studied examination responses from groups of university students who had completed a course on introductory physics, including electrical circuits and Ohm's

Law. The students were presented with an exam question about a simple DC circuit. Although the students had the necessary mathematical skills and had previously used Ohm's Law to solve more complex circuit problems, only 10-15% of them answered the question correctly. McDermott found that many students failed because they held misconceptions (e.g., "current is used up by the bulbs in the circuit"), misunderstood concepts (e.g., equivalent resistance), used concepts incorrectly, or lacked a conceptual model that would enable them to make qualitative predictions about the behavior of circuits. She observed that when "[f]aced with a simple but unanticipated situation, the students could not do the necessary reasoning" (p. 308). In another study, McDermott and Shaffer (1992) observed that many students have persistent conceptual difficulties with analyzing simple electrical circuits, such as an inability to apply formal concepts related to current, voltage, and resistance (e.g., a failure to distinguish between equivalent resistance of a network and the resistance of individual elements; the belief that direction of the current and order of elements matter; and difficulty identifying series and parallel connections). Moreover, they observed that many students fail to synthesize basic electrical concepts into a coherent framework. As a result, these students lack a conceptual model and are unable to reason qualitatively about the behavior of electrical circuits. For example, when a change is made in a circuit, students often tend to focus their attention only on the point where the change occurs, not recognizing that a change made at one point in a circuit may result in changes at other points. These observations still hold today; in more recent literature about electricity instruction it is remains the case that students fail to acquire a deep conceptual understanding of electricity and the behavior of electrical circuits (see e.g., Başer & Durmuş, 2010; Başer & Geban, 2007; Glauert, 2009; Gunstone, Mulhall, & McKittrick, 2009; Hart, 2008; Jaakkola, Nurmi, & Lehtinen, 2010; Jaakkola, Nurmi, & Veermans, 2011; Streveler, Litzinger, Miller, & Steif, 2008; Zacharia, 2007).

A proper conceptual understanding enables students to reason about potential differences, voltage at different locations within a circuit, and the flow and the intensity of current (Cohen, Eylon, & Ganiel, 1983; Frederiksen et al., 1999; Streveler et al., 2008). Streveler et al. (2008) argue that conceptual understanding in the engineering sciences includes both knowledge about quantities (such as current and potential difference) and knowledge about the relationships among these quantities (e.g., as expressed by Ohm's Law). They follow the more general definition provided by Rittle-Johnson, Siegler, and Alibali (2001), who define *conceptual understanding* as "implicit or explicit understanding of the principles that govern a domain and of the interrelations between units of knowledge in a domain" (p. 346-347). Swaak and de Jong (1996, 2001) argue that as students' conceptual understanding becomes deeper, the accuracy with which they can assess the causal relations between quantities in problem situations will increase, as will the accuracy of their predictions of how these quantities will respond to changes.

Conceptual understanding is a critical element in the competence and expertise of engineering students and practicing professionals (Streveler et al., 2008). Yet a correct and deep conceptual understanding of electricity does not seem to emerge in traditional instruction. Before moving on towards possible solutions, the next section will first focus on current practices in traditional electricity instruction.

Traditional instruction on electrical circuits

Traditionally, in vocational engineering education, curricula about electrical circuits have two components: textbook-based instruction and practical, hands-on lessons. In the textbooks, the subject matter is often approached from a factual and calculus-based angle. Students are presented with facts, definitions, and laws, and they are taught equations (e.g., based on Ohm's Law, $I = V/R$) that can be used to solve standard circuit problems (Frederiksen et al., 1999; Gunstone et al., 2009; Jaakkola et al., 2011; McDermott & Shaffer, 1992)., Therefore, textbooks and the exercises in the textbooks often emphasize procedural skill, which is “the ability to execute action sequences to solve problems” (Rittle-Johnson et al., 2001, p. 346) and the reproduction of facts and definitions.

These textbook-based lessons are often supplemented with practical lessons in which students can build electrical circuits and carry out measurements. These practical lessons are essential for developing skills and experience with working with real equipment and, through experimentation, a conceptual understanding of the domain. However, practical lessons also have limitations that in general keep students from developing a proper conceptual understanding. For example, in practical lessons students tend to focus on making their circuits work rather than on trying to understand the causal relations between variables and outcomes (Schauble, Klopfer, & Raghavan, 1991). Furthermore, when working with real circuits students must deal with all kinds of unexpected circumstances (dim bulbs misinterpreted as unlit (Finkelstein et al., 2005)) and deviations from what they have learned in the textbook-based lessons. For example, in reality equipment (circuits, resistors, wires, batteries) is not ideal, and consequently the measurements in the circuits will show different outcomes than expected purely on the basis of formulas. Furthermore, students often do not engage in systematic experimentation and they rarely if ever link their hands-on activities with what they have learned in the textbook lessons.

The observation that the acquisition of conceptual understanding in traditional vocational curricula is problematic suggests that this combination of textbook-based instruction and practical lessons does not provide students with optimal conditions for acquiring proper conceptual understanding of electricity and electrical circuits. If traditional vocational instruction is less than suitable for fostering the acquisition of conceptual understanding, adding learning opportunities that foster conceptual understanding to the curriculum seems a logical next step.

Fostering the acquisition of conceptual understanding in electricity instruction

Papadouris and Constantinou (2009) argued that the accumulation of experiences with natural phenomena through active exploration, investigation, and interpretation provides a basis for the development of conceptual understanding. The role of active experimentation by students in science learning was also emphasized by Steinberg(2000). In his opinion there are at least two elements that appear to be critical in making science instruction successful. First, successful instruction is based on understanding how students make sense of the subject matter. That is, instruction must take into account the ideas and conceptions the students already have about the subject matter. As stated in the introduction, electricity is an abstract and intangible concept; however, most people have conceptions, often pre-scientific and idiosyncratic ones, about what electricity is and how electricity “behaves”. Steinberg emphasizes the importance for instruction of helping students to “elicit” their own conceptions and using those conceptions as a starting point for the instruction. Second, students must be actively engaged in finding out what is happening instead of just witnessing something being presented. They need to make predictions, design experiments, analyze and interpret the collected data, and formulate answers to their research questions; in other words, they must be engaged in a process of inquiry learning (see e.g., Chi, Slotta, & de Leeuw, 1994; Chinn & Brewer, 1998; Hewson, 1985; Jaakkola et al., 2010; Muller, Bewes, Sharma, & Reimann, 2008; Strike & Posner, 1985; Tao & Gunstone, 1999; Trundle & Bell, 2010; Zacharia, 2007).

In inquiry learning, students learn through exploration and application of scientific reasoning. It has been found to be among the most effective methods for acquiring conceptual knowledge (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Deslauriers & Wieman, 2011; Eysink et al., 2009; Prince & Felder, 2006). Computer technology can support inquiry learning by students and facilitate the inquiry learning process in many ways, such as by offering computer simulations for exploring, experimenting, and collecting empirical data (de Jong, 2006; de Jong & van Joolingen, 1998; Park, Lee, & Kim, 2009; Rieber, Tzeng, & Tribble, 2004; Trundle & Bell, 2010).

Simulations contain models that are designed to simulate systems, processes, or phenomena. Students can change the values of variables in the simulation (e.g., the resistance in a virtual electrical circuit) and observe the effects of those changes on other variables (e.g., voltage or current). The simulations allow students to conduct experiments and collect experimental data quickly and easily. (In this sense the simulation could also be called a virtual laboratory, and therefore henceforth the term "virtual lab" will be used.) Building or adjusting experimental setups with real equipment can be laborious and time-consuming. In a virtual lab, in contrast to a real lab as described above, the setup can be given and changes to the configuration can be made quickly and effortlessly, allowing students to focus and to stay focused on their inquiry processes without delay or disruption. By systematically changing variables and observing and interpreting the consequences of those changes, the students can explore the properties of the underlying model (e.g., Ohm's Law) (de Jong, 2005, 2006; de Jong & van Joolingen, 1998). Furthermore, seeing what "happens in reality" can support students with testing the validity of their own mental model and with identifying aspects of their model that need to be refined. Eventually, this can help students to bring their mental models in line with the real phenomena (Papadouris & Constantinou, 2009; White & Frederiksen, 1998).

Although active engagement and meaningful learning are viewed as primary characteristics of inquiry learning with virtual labs (Svinicki, 1998), meaningful learning may not result simply from behavioral activity per se. Mayer (2002, 2004) suggests that only specific cognitive activities (e.g., selecting, organizing, and integrating knowledge) may promote meaningful learning. In order to ensure that students deploy the required and appropriate cognitive activities and to prevent them from floundering, guidance is necessary (de Jong, 2005, 2006; de Jong & van Joolingen, 1998; Quintana et al., 2004; Reiser, 2004; Sharma & Hannafin, 2007). Integrating supportive cognitive tools within the learning environment can guide students through their inquiry processes (de Jong, 2006). For example, regular inquiry process components, such as orientation (identification of variables and relations), hypothesis generation, experimentation (changing variable values, making predictions, and interpreting the outcomes), reaching conclusions (hypothesis testing), and evaluation (reflection on the learning process and the acquired knowledge) can be embedded in assignments. Computers can give feedback to students if their responses to assignments are incorrect (Steinberg, 2000).

The idea of using virtual laboratories in electricity instruction is not new. Previous studies have indicated that learning with virtual labs or computer simulations can have a positive effect on the acquisition of conceptual knowledge in the domain of electricity and simple electrical circuits when used as a substitute for real equipment (see e.g., Başer & Durmuş, 2010; Farrokhnia & Esmailpour, 2010; Finkelstein et al., 2005; Jaakkola & Nurmi, 2008; Jaakkola et al., 2010; Jaakkola et al., 2011; Zacharia, 2007). These studies focused on elementary school children (Jaakkola & Nurmi, 2008; Jaakkola et al., 2010; Jaakkola et al., 2011), pre-service elementary school teachers (Başer & Durmuş, 2010), and university students (Farrokhnia & Esmailpour, 2010; Finkelstein et al., 2005).

In the current study we focus on a different type of students, namely students from secondary vocational engineering education. Vocational education is more concrete in nature compared to general types of education. In vocational education students are trained for clearly defined professions or tasks (e.g., becoming mechanics, electricians) (Slaats, Lodewijks, & van der Sanden, 1999). In the Netherlands, an achievement test known as the ‘CITO-test’ (the Central Office for Standardised Testing) is administered to all pupils at the end of their primary education. On the basis of their test scores the pupils are tracked into either pre-vocational education or general (higher or pre-university) education. A little more than 60% of the students are tracked into pre-vocational education (12- to 16-year-olds) and then secondary vocational education (16- to 20-year-olds) (Meijers, 2008). Inquiry learning is often assumed to be too demanding for these students, because it requires them to adopt a scientific approach. Vreman-de Olde (2006) characterizes students in secondary vocational training as ‘do-ers’, who have a visual orientation and who are mostly interested in the practical application of their knowledge. They learn by experience and have difficulty with abstract theoretical models and methods (Slaats et al., 1999). In particular, these students find the domain of electricity to be abstract. Vreman-de Olde (2006) suggests that using realistic visualizations in computer simulations (or virtual labs) can support these students in connecting reality and theoretical concepts. Working with real laboratories is also a necessity for these students, because they will work with similar equipment in their professional lives. Therefore, in the current study we did not replace the practical lesson with a real laboratory but instead gave students additional lessons in a virtual lab.

The main question addressed in the current study is: how can the acquisition of conceptual understanding be fostered in electricity instruction that occurs in the context of secondary vocational engineering education? The current study compares two experimental conditions: one condition in which students followed traditional instruction supplemented with inquiry learning within a virtual lab, and one condition in which students followed traditional instruction only (supplemented with additional traditional (computer-based) practice). The lessons involved were an integral part of a complete electricity curriculum (including both textbook and practical lessons) in the context of intermediate level vocational engineering training.

Method

Participants

In total, 56 students in intermediate level vocational engineering training participated, all boys (no female students were enrolled in the engineering courses). The study was approved by the school board and the participants' parents. As will be further explained in the next section there were two conditions, the traditional condition and the virtual lab condition. Thirteen participants dropped out: four dropped out of school during the period in which the experiment took place (one in the traditional condition and three in the virtual lab condition); four missed more than half of the sessions (two in the traditional condition and two in the virtual lab condition); and five were unable to attend the post-test session (two in the traditional condition and three in the virtual lab condition). The ages of the 43 remaining students (23 in the traditional condition and 20 in the virtual lab condition) ranged from 16 to 22 years old (M = 19.17; SD = 1.39).

Design

A between-subjects design was used in the experiment, with the Instructional method (traditional instruction plus extra computer-based practice (traditional condition) versus traditional instruction plus inquiry learning within a virtual lab (virtual lab condition)) as the independent variable. Participants were randomly assigned to either the traditional condition or the virtual lab condition. Students in both conditions followed the same curriculum, the full regular electricity curriculum. This curriculum in which the experiment was embedded contained the following courses: a textbook-based course, "Electricity Theory", and two practical courses, "Measuring Electricity" and "Workplace Practice". The courses in the curriculum lasted three months or more. The time span of the experiment was nine weeks, with one session every week. These nine sessions formed a relatively small part compared to the entire electricity curriculum, but the experiment only aimed to cover the period during which simple DC circuits were treated in the regular curriculum. In the traditional condition, the traditional instruction was supplemented with additional practice (based on traditional instruction) on topics treated in the main curriculum. In the virtual lab condition, the traditional instruction was supplemented with inquiry learning in a virtual lab, also on the topics treated in the main curriculum. Except for these nine sessions, all courses and activities were the same for all participants.

Learning environments

The regular curriculum that the students follow includes topics such as energy sources, resistance, circuits, Ohm's Law, Kirchhoff's Laws, alternating current, and magnetic fields. In this curriculum students have textbook and practical (lab) lessons. The emphasis in the textbook lessons is on facts, definitions, formulas, and procedural skills (calculating parameters such as voltage, current, resistance, and power); in the practical lessons students practice building electrical circuits and performing electricity measurements in these circuits. Two books are used: a textbook (Frericks & Frericks, 2003) in which facts, definitions, and formulas are presented and procedures are explained, and an exercise book (Frericks & Frericks, 1998) with chapters that correspond to the chapters in the textbook. These chapters briefly repeat the topics treated in the textbook, provide more in-depth explanations of procedures, and offer questions (about facts and definitions) and assignments in which students are required to calculate parameters. The experiment covered part of the topics treated in the regular curriculum, namely electrical circuits (series, parallel, and mixed connections), Ohm's Law, and some elements of Kirchhoff's Laws. Two computer-based learning environments were used in the experiment, one for each condition.

Learning environment used in the traditional condition

The traditional condition included use of a computer-based learning environment that was developed and produced by the same company that published the textbook and exercise book described above. The software was meant as additional practice material (although the participating school did not use this software in the regular curriculum). The software offered a brief summary and a series of exercises for each chapter of the textbook and exercise book, mainly calculation exercises, but also some insight questions (measured by means of multiple choice items). After completion of each exercise, students received feedback about the correctness of their response as well as an explanation of the correct answer. At the end of each chapter the system informed the student about the percentage of correct responses for that chapter.

Learning environment used in the virtual lab condition

Participants in the virtual lab condition were provided with a virtual lab-based inquiry learning environment. This was created by the authors with SIMQUEST authoring software (de Jong et al., 1998; Swaak & de Jong, 2001; van Joolingen & de Jong, 2003). The virtual lab environment presented photographic images of equipment used in the school's practical (lab) courses about electricity (see Figure 1).

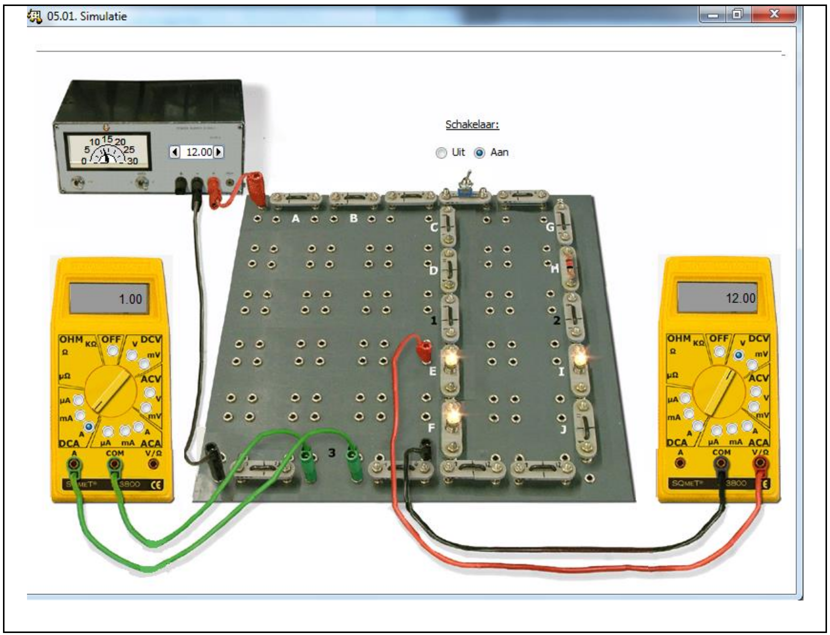


Figure 1. Screen dump of virtual lab

In the virtual lab environment the students were presented with electrical circuits. They could add or remove electrical components (e.g., light bulbs, resistors, LED's), adjust the voltage, and perform measurements using virtual measuring equipment to measure (changes in) voltage across components and the strength of the current flowing through different parts of the circuit. The images of real equipment made the virtual lab highly realistic.

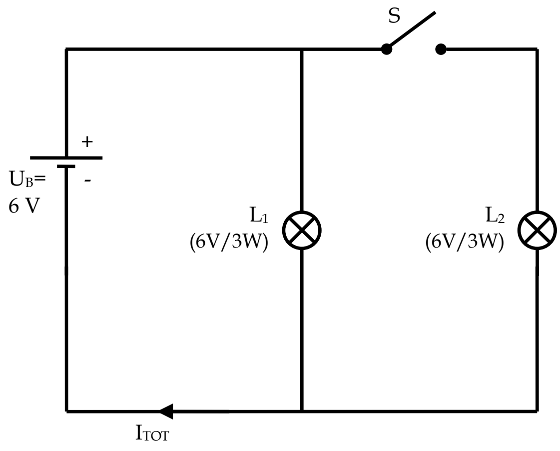
As indicated in the introduction, students need instructional guidance in order to make inquiry learning within a virtual lab effective. In the current study students were provided with assignments that were integrated within the virtual lab environment, and that were designed to structure their experimentation processes. Such assignments have been found to be a successful type of instructional guidance in inquiry learning (Swaak, van Joolingen, & de Jong, 1998). In the current study, these assignments had the following structure: first, the student was asked to predict the outcome of a change in a circuit,e.g., "In a series connection there is one component, a light bulb (6V/3W). The voltage applied across this bulb is 6V. Suppose a second bulb is added to the connection. What will happen to the voltage across the first bulb (all else being equal)?". This part of the assignment was meant to activate prior knowledge and to have students articulate their own, idiosyncratic conceptions (or misconceptions) about the domain. Then the participants could use the virtual lab to experiment, that is, to collect empirical data, and make observations that would help them to find out what really happens in the situation described in the first step. After the second step, the participants were asked to reflect upon the correctness (or incorrectness) of their initial prediction and to draw conclusions on the basis of their observations in the virtual lab.

Knowledge measures

Two knowledge tests were used in the experiment: a prior knowledge test and a post-test. The prior knowledge test was an entrance test that contained 27 items and aimed at measuring (possible differences in) the prior knowledge of the students. The post-test contained 19 items and was meant to measure the effects of instructional method on learning outcomes. The prior knowledge test contained 14 conceptual and 13 procedural items. The post-test contained 14 conceptual items and 5 procedural items. Because the depth of understanding required to answer problems depends on their level of complexity, we included both simple and complex items on the post-test.

Conceptual and procedural items

In the introduction it was argued that a proper conceptual understanding enables students to reason about potential differences and the flow and the intensity of current (Cohen, Eylon, & Ganiel, 1983; Frederiksen, et al., 1999; Streveler, et al., 2008). Therefore, the conceptual items on the test required participants to reason about the behavior of current and potential difference in various DC circuits, including series, parallel, and mixed connections. (At this stage, the curriculum and the textbook treated resistance as a constant.) In some conceptual items participants were given two circuits (e.g., one circuit with two light bulbs in a series connection, and one circuit with two light bulbs in parallel) and then they had to reason about how a specific variable (e.g., current) would behave in the different circuits. In other conceptual items participants were given a circuit in which a certain change took place (e.g., turning a switch on or off). Then they had to reason about how this change in one parameter would affect other parameters. An example of a conceptual item is shown in Figure 2.

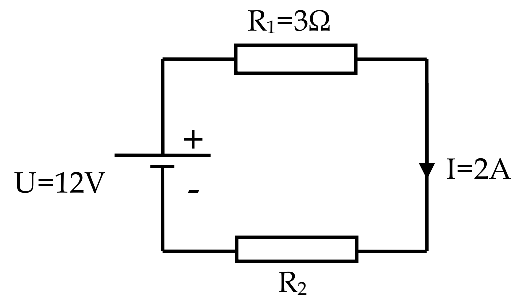


Given the circuit displayed above. Light bulb L_1 is shining. Peter is measuring the current at I_{TOT}. When switch S is turned on, Peter notices that the current remains unchanged. Why is that?

Figure 2. Post-test item (conceptual understanding)

Several principles need to be taken into account when solving the problem displayed in Figure 2: (a) when switch S is turned on, the simple connection actually becomes a parallel connection; furthermore, under normal conditions (b) the voltage across light bulb L_1 remains unchanged when the circuit switches from a simple to a parallel connection; (c) the voltage across the two parallel trajectories will be equal; (d) the total (equivalent) resistance will change; (e) therefore so will the current (Ohm’s Law). The information that the current at I_{TOT} remains unchanged after switch S is turned on therefore indicates that the circuit is not behaving normally. In fact, the circuit keeps behaving as it did when switch S was still turned off. Apparently, there is some blockage in the parallel trajectory; perhaps one of the components (e.g., switch S or light bulb L_2) is broken.

The procedural skills items on both the prior knowledge test and the post-test were based on test items designed and used by teachers in previous years in the Electricity Theory course. All procedural items presented participants with a given circuit and required them to calculate the value of a specific variable (e.g., resistance, voltage, or current). Figure 3 shows an example of a procedural item.



Given the circuit displayed above.
Calculate the resistance of R_2 (in Ω).

Figure 3. Post-test item (procedural skills)

Like the previous problem, the problem displayed in Figure 3 requires multiple principles to be applied in order to find the solution. One principle is Ohm's Law (I =V/R) to determine the total amount of resistance in the circuit. The total resistance is 12V/2A = 6Ω. There are two resistors in the circuit. The second principle that must be applied is the principle that in a series connection such as the given circuit, the resistances of different components (e.g., resistors) add up. One resistor (R_1) is 3Ω, and therefore the resistance of the other (R_2) must be the total resistance minus the resistance of R_1, 6Ω - 3Ω = 3Ω.

Problem complexity

Problems and solutions that involved two or more principles were considered complex problems. Problems that required the application of only one principle (e.g., Ohm's Law) were considered simple problems. Around 40 percent of the post-test items were complex, so that a differential effect of treatment in relation to level of complexity could be assessed. The two items discussed in the previous section (see Figure 2 and Figure 3) both required the application of multiple principles in order to be solved. The distribution of post-test items over the different categories of knowledge type and complexity is displayed in Table 1.

Table 1
Distribution of post-test items by knowledge type (conceptual or procedural) and complexity (simple or complex)

		Complexity	
		Simple	Complex
Knowledge type	Conceptual	8	6
	Procedural	3	2

Examination results

At the end of the semester, the school provided the experimenters with the participants' examination results in the following related curricular courses: Electricity Theory, Measuring Electricity, and Workplace Practice. In the course *Electricity Theory*, students were presented with facts, definitions, laws, and theories, and they were taught equations that could be used to solve standard circuit problems. In the practical course *Measuring Electricity*, the students had to put components in electrical circuits following recipe-like instructions and then they had to perform measurements in those circuits. In the practical course *Workplace Practice,* students had to design and build electrical circuits.

Procedure

The experiment was carried out in a real school setting. In both conditions, the time taken for the experimental sessions was in addition to that devoted to the regular curriculum. There were nine sessions in total, including a prior knowledge test session and a post-test session. Sessions were separated by one-week intervals. In the first session, which took about 90 minutes, the students received some background information about the purpose of the study, the domain of interest, learning goals, and so on. This was followed by the prior knowledge test. In the second session, participants were randomly assigned to one of the experimental conditions. After this, both groups were directed to separate classrooms. (The experimental instructional sessions all took place in two different classrooms: one for each condition.) The rest of the second session was spent teaching participants how to operate their assigned learning environments. Following this introduction to the assigned learning environments, students in both conditions participated in six content-related instructional sessions, each lasting 45 minutes. Students felt this amount of time on the topic was sufficient. During these sessions the participants in both conditions worked on their own (one participant per computer) and at their own pace through the chapters and assignments in their learning environment. In the ninth, final session, the participants completed the post-test. The duration of this session was also 45 minutes; all students were able to finish the post-test within this time. APA standards for the ethical treatment of human participants were followed.

Results

Prior knowledge

The scores on the prior knowledge test are displayed in Table 2.

Table 2
Prior knowledge test scores on conceptual and procedural items

	Condition							
	Traditional (n = 23)				Virtual lab (n = 20)			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Conceptual test (max. 14)	5.26	2.70	1	12	5.90	2.95	1	12
Procedural test (max. 13)	5.17	1.75	1	8	4.85	2.51	0	9
Total (max. 27)	10.43	3.03	4	17	10.75	3.73	4	19

Independent samples T-tests performed on the prior knowledge test scores established that there were no differences between conditions: conceptual understanding, t (41) = - 0.74, *n.s.*; procedural skills, t (41) = 0.50, *n.s.*; total prior knowledge test score, t (41) = - 0.31, *n.s.* It can therefore be assumed that students in both conditions had comparable levels of prior knowledge.

Post-test

The post-test scores on conceptual and procedural items are displayed in Table 3.

Table 3
Post-test scores on conceptual and procedural items

	Condition							
	Traditional (n = 23)				Virtual lab (n = 20)			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Conceptual test (max. 14)	4.09	1.83	1	9	5.35	2.03	1	8
Procedural test (max. 5)	2.96	0.93	1	5	3.65	0.88	2	5
Total (max. 19)	7.04	1.82	4	12	9.00	2.20	5	12

Prior knowledge scores were entered as covariates in the analyses of post-test scores. It was found that students in the virtual lab condition obtained significantly higher *overall scores* (F (1, 40) = 9.82, $p < 0.01$) than participants in the traditional condition. The effect size (Cohen's d = 0.98) indicates that this is a strong effect. Participants in the virtual lab condition also scored significantly higher on *conceptual items* (F (1, 40) = 4.12, $p < 0.05$). The effect size (Cohen's d = 0.65) shows that this can be considered a medium effect. Participants in the virtual lab condition obtained significantly higher scores as well on the *procedural items* (F (1, 40) = 5.93, $p < 0.05$), The effect size (Cohen's d = 0.76) indicates that this is a large effect.

The procedural skills items were based on test items designed and used by teachers in previous years in the Electricity Theory course. Therefore, a correlation between scores on the post-test procedural skills items and examination grades for Electricity Theory was to be expected. This was confirmed by the data ($r = .52$, $p < 0.01$) (see also Table 5). The conceptual items were developed for the current study, and therefore their reliability still had to be established. The internal consistency measure, Cronbach's alpha, for the conceptual knowledge scale was .43. This value suggests that conceptual understanding in this situation has many different facets, including understanding of different variables such as current and potential difference, along with knowledge about how each of these behaves in different circuits (e.g., in series, parallel, or mixed connections). If conceptual items about current are considered as one subscale and conceptual items about potential differences as another subscale, the internal consistency values rise to 0.57 and 0.67, respectively; however, these subscales are still estimates because they do not differentiate between types of circuits.

Besides the conceptual-procedural distinction, post-test items can also be distinguished on the basis of the complexity of their solutions. Problems that required the application of only one principle in solving them were considered simple problems, while those that required multiple principles for their solution were considered complex items. The data regarding scores on simple and complex items are presented in Table 4.

Table 4
Post-test scores on simple and complex items

	Condition							
	Traditional (n = 23)				Virtual lab (n = 20)			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
Simple items (max. 11)	5.30	1.43	2	8	5.75	1.71	2	8
Conceptual (max. 8)	3.09	1.41	0	6	3.45	1.57	0	6
Procedural (max. 3)	2.22	0.52	0	3	2.30	0.66	1	3
Complex items (max. 8)	1.74	1.21	0	4	3.25	1.33	1	6
Conceptual (max. 6)	1.00	1.24	0	4	1.90	1.29	0	5
Procedural (max. 2)	0.74	0.75	0	2	1.35	0.67	0	2
Total (max. 19)	7.04	1.82	4	12	9.00	2.20	5	12

No differences between conditions were observed with regard to scores on simple problems (*t* (41) = - 0.93, *n.s.*). However, with regard to complex items, a significant difference was found between conditions. Participants in the virtual lab condition were more successful in solving complex problems (t (41) = - 3.89, $p < 0.0001$). The effect size (Cohen's $d = 1.19$) shows that this is a large effect.

In Table 4 both the simple and complex item scores are also specified in terms of conceptual understanding and procedural skills. There were no differences between conditions with regard to scores on simple conceptual items (t (41) = - 0.80, *n.s.*) or simple procedural items (t (41) = - 0.46, *n.s.*). The participants in the virtual lab condition were more successful in solving complex conceptual problems (t (41) = - 2.32, $p < 0.05$). The effect size (Cohen's d = 0.71) indicates that this is a medium effect. The participants in the virtual lab condition were also more successful in solving complex procedural problems (t (41) = - 2.79, $p < 0.01$). This effect size was Cohen's $d = 0.86$, which is a large effect.

The place of conceptual knowledge in the curriculum

We began this article by stating that traditional instruction is not very well suited to helping students acquire conceptual understanding. In the following analyses we explore the relations among type of instruction, conceptual understanding, and procedural skills. The first analysis involves the correlations between post-test scores and other examination scores (see Table 5). The correlations in the table are the total correlations. Correlational analyses were also run for each condition separately, but yielded results very similar to those in Table 5.

Table 5
Correlations between post-test scores and examination results for the other curricular activities

	1	2	3	4	5
Traditional instruction exam results					
1. Electricity Theory	-				
2. Measuring Electricity	0.36*	-			
3. Workplace Practice	0.19	0.37*	-		
Post-test scores					

4. Conceptual understanding	0.10	- 0.11	- 0.22	-	
5. Procedural skills	0.52**	0.18	0.45**	0.01	-

* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Of interest in Table 5 is that conceptual understanding as measured in the post-test turns out to be unrelated to the examination results obtained in the other curricular activities. Procedural skills as measured in the post-test are related to performance in the Electricity Theory part of the curriculum (traditional instruction) and Workplace Practice.

To further explore these relations, we ran a principal component analysis of post-test scores and examination results. The results are displayed in Table 6. Principal component analyses were run for each condition separately as well, but since they yielded very similar results, we will discuss the analysis for the sample as a whole.

Table 6
Component loadings

	Components		
	1	2	h^2
Electricity Theory	**0.71**	0.46	0.72
Measuring Electricity	**0.65**	- 0.14	0.44
Workplace Practice	**0.72**	- 0.37	0.65
Conceptual understanding	- 0.16	**0.87**	0.77
Procedural skills	**0.77**	0.21	0.63
Eigenvalue	2.05	1.16	

Note. Component loadings were obtained using principal component analysis.

As can be observed in Table 6, two components were detected. From these results it becomes clear that conceptual understanding is a separate aspect of knowledge that is different from the knowledge acquired through the traditional curricular activities. The loadings on the first component showed that examination results for these traditional activities (Electricity Theory, Measuring Electricity, and Workplace Practice) are intimately tied together, and largely belong to one and the same component. Scores on the procedural skills items, which all involved calculating basic parameters, such as voltage, current, and resistance, also loaded heavily on this first component. This component can therefore possibly be interpreted as a kind of (procedural) domain understanding that allows students to perform procedures and to solve computational problems. Conceptual understanding, which was measured by items that all involved reasoning about the behavior of electrical circuits, loaded heavily on the second component. The emergence of this second distinct component confirmed that conceptual understanding as we operationalized it in this study is a unique, separate, element.

Discussion and conclusions

The main question addressed in this study was: how can the acquisition of conceptual understanding about electricity be fostered in the context of secondary vocational engineering education? Two conditions were compared to each other in an experimental setup. In both conditions, students followed the same traditional electricity curriculum. In the traditional condition the traditional instruction was supplemented with additional, computer-based practice about topics treated in the basic curriculum. In the other condition the traditional instruction was supplemented with inquiry learning within a virtual lab, again about the topics treated in the main curriculum.

Post-test results showed that participants in the virtual lab condition outperformed participants in the traditional condition on conceptual understanding. One could argue that if participants in the traditional condition had had more time and practice, perhaps their conceptual understanding might finally have reached the level of understanding of their colleagues in the virtual lab condition. However, the data indicate that the key does not seem to lie in extra time and practice. Principal component analysis of the scores on conceptual understanding, procedural skills, and the examination results of the other curricular activities showed that procedural skills scores and the examination results for the other curricular activities all loaded heavily on one component, indicating they are all largely co-determined.

The factor loading of conceptual understanding on this component was very low. And the other way around, conceptual knowledge loaded heavily upon a second component, whereas procedural skills scores and examination results showed only low factor loadings on this second component. This result indicates that conceptual understanding is fundamentally different from other knowledge and skills that the students acquire in the electricity curriculum.

Participants in the virtual lab condition also outperformed participants in the traditional condition with regard to procedural skills. This finding was unanticipated, because all assignments that were included in the virtual lab aimed at making and testing qualitative predictions about the behavior of electrical circuits; none of those assignments targeted the acquisition or practice of procedural skills. The finding that also procedural skills improved, could be an indication that in the virtual lab condition bootstrapping (Schauble, 1996) or iterative knowledge development (Rittle-Johnson et al., 2001) processes took place, that is, the idea that the acquisition of conceptual understanding and other forms of knowledge and skills (e.g., procedural skills) can mutually support and stimulate each other. An increase in one type of knowledge facilitates an increase in the other type of knowledge, which facilitates an increase in the first, and so on. The existence of interrelations between procedural and conceptual knowledge has been presumed for decades. For example, conceptual knowledge helps learners to recognize and identify key concepts when studying or diagnosing a problem. As a result, a better conceptual understanding of the problem will increase the likelihood that the learner will select the appropriate problem solving procedure (enhancing procedural skills). In turn, reflecting on or self-explaining the conceptual basis of procedures can help learners to become aware of which concepts play a key role in a problem (Rittle-Johnson et al., 2001). Some evidence for bootstrapping has been found in the domain of mathematics, but not so far in engineering education (Streveler et al., 2008).

This interplay between conceptual and procedural knowledge will become most evident when solving complex problems. Items on our post-test that required the application of only one principle in solving them were considered simple problems; items that required multiple principles for their solution were considered complex items. It was found that participants in the virtual lab condition scored significantly better on solving complex problems, both complex conceptual and complex procedural problems. Students in the traditional condition had more difficulty when two or more principles had to be taken into account simultaneously. This could be an indication that learners in the virtual lab condition had better synthesized the basic electrical concepts into a coherent framework.

In the current study we did not replace practical lessons with inquiry learning in a real laboratory, but gave students additional experimentation experience in a virtual lab. Handling real equipment in real laboratories is also necessary for these students, because they will work with similar equipment in their professional lives. An obvious question would be: can inquiry learning be integrated into the practical, real lab lessons; that is, can the virtual lab be replaced by the real lab? And conversely, could the virtual lab replace the real lab? In some studies comparing learning in real labs to learning in virtual labs, equivalent learning results were found (e.g., Triona & Klahr, 2003; Zacharia & Constantinou, 2008). In other studies, learning in virtual labs has been found to be more effective than learning in real labs (e.g., Bell & Trundle, 2008; Chang, Chen, Lin, & Sung, 2008; Finkelstein et al., 2005; Huppert, Lomask, & Lazarowitz, 2002). However, we would not recommend choosing between real or virtual labs. Now that the beneficial effects of inquiry learning in a virtual lab have been established in the context of secondary vocational engineering education, we would instead suggest as a next step to shift the focus towards supporting inquiry learning by using a combination or sequence of both virtual and real labs. Other empirical studies have shown that such a combination or sequence (e.g., first learning in a virtual lab, followed by learning in a real lab) can lead to better conceptual understanding than using a virtual lab or a real lab alone (Jaakkola & Nurmi, 2008; Jaakkola et al., 2010; Jaakkola et al., 2011; Zacharia, 2007).

An issue that needs to be addressed is the ecological validity of the study. The experiment was integrated into an existing curriculum and the experimental sessions took place in the school during regular school time. On the one hand, this helps to guarantee the ecological validity of the study and its results, but on the other hand, it makes it hard to maintain strict experimental rigor during the experiment. For example, in the school setting it is impossible to keep participants from both conditions isolated from each other for nine weeks. Of course, the participants were in two separate computer classrooms during the experimental sessions, one room for each condition, but the participants could not be kept separated during the other school hours. The possibility that participants "mixed", which could muddy the effects, cannot be ruled out. Yet, for two reasons we believe that it is unlikely that this actually happened. First, outside the classrooms (e.g., during breaks) these students talk about a lot of things, but hardly about subject matter treated in the classrooms. Second, one would suppose that muddying the effects because of mixing would lead to more equal post-test scores for both conditions. Therefore, if muddying took place in our study this would mean that the effects that were observed in this study are actually an underestimation of the 'true' effects. Being an underestimation or not, the ecological validity helps to establish the value of inquiry learning within a virtual lab by showing that the beneficial effects can actually be observed in the daily practice of the school.

On the basis of the current study we can recommend that teachers in vocational education about electricity who want to stimulate conceptual understanding should supplement or perhaps interweave their traditional approach with inquiry learning within a virtual lab. It is often assumed that this is too demanding for students of this level, but our study shows that if the inquiry component is well-supported it will also work in vocational training settings.

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