Efficacy of a Virtual Teaching Assistant in an Open Laboratory Environment for Electric Circuits

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ABSTRACT

In order to provide an on-demand, open electrical engineering laboratory, we developed an innovative software-based Virtual Open Laboratory Teaching Assistant (VOLTA). This web based virtual assistant provides laboratory instructions, equipment usage videos, circuit simulation assistance, and hardware implementation diagnostics. VOLTA allows students to perform laboratory experiments anywhere at their convenience. A series of studies was carried out in an experimental section of our traditional entry-level electric circuits laboratory to answer the hypothesis: students taught using VOLTA will learn as much as students who were taught by a human teaching assistant. The experiments were conducted using a pre-test/post-test design, and student performance was assessed using ANOVA on gain scores. Statistical analysis revealed that the student performance increased significantly when VOLTA was integrated into a closed laboratory. We conclude that VOLTA can support students in open and closed laboratories as effectively as a human teaching assistant.

Key words: Virtual Teaching Assistant, Open Laboratory, Distance Learning, Internet-based instruction, Electrical Engineering.

INTRODUCTION

Laboratories play an important role in undergraduate engineering education. The purpose of these laboratories is to reinforce classroom learning with hands-on experience to enhance students'

understanding of real world engineering problems (Ernst, 1983; Feisel & Rosa, 2005). Traditionally, students conduct experiments in the laboratory on a fixed schedule under supervision of a teaching assistant. Such a format is often referred to a "closed laboratory" (Palais & Javurek, 1996). Closed laboratories have space and time constraints and do not offer students the flexibility needed to enhance the learning process. For example, students often work in groups because expensive laboratory equipment is in short supply. Not all students receive adequate instruction due to the limited availability of teaching assistants. Many students find it difficult to meet with their instructor or teaching assistant during office hours due to scheduling constraints. In a closed laboratory paradigm, students follow very specific instructions (often referred to as lockstep instruction) for a predetermined period of time without considering the relationship between the hands-on experiment and their classroom instruction. A laboratory assignment is viewed as mindless routine work and does not foster critical thinking in students (Knight & DeWeerth, 1996). For effective use of resources and to optimize the learning environment for students in laboratories, researchers have been investigating many alternative learning approaches over the past three decades. An open laboratory is one such popular approach.

An open laboratory, in which students can conduct their experiments at any time, mitigates the scheduling and resource utilization issues (Palais & Javurek, 1996; Oswald & Sloan, 1971; Kuhn et al., 2000). Students can repeat experiments to achieve a better understanding of the material. Students must demonstrate mastery before they can proceed to the next experiment. An open laboratory promotes self-directed learning that is crucial to long-term retention of knowledge (Litzinger et al., 2005; Jiusto & DiBiasio, 2006).

However, providing instructional support for an open laboratory using the traditional teaching assistant model is challenging. Virtual teaching assistants are a viable option but as yet have not been developed for open laboratories. In order to circumvent this problem, we developed a virtual teaching assistant for offering on-demand help to the students in an open laboratory. The system is called Virtual Open Laboratory Teaching Assistant (VOLTA). This web-based system is equipped with pre-laboratory instructions, equipment usage videos, topic-based explanations, and assistance for performing circuit simulations and hardware implementations.

The open laboratory concept is not entirely new. Oswald and Sloan (1971) published a study on an open laboratory for a senior electronics laboratory at Michigan Technological University. Students could schedule their laboratory time in two-hour blocks and perform experiments without direct supervision. In their opinion, although the instructor time did not increase, the effectiveness of instructor time increased. However, they could not reduce the time required to grade laboratory reports. Their approach eliminated the problem of a group being dominated by a single student and provided slower students the opportunity to acquire necessary experience. The Oswald and Sloan study did not include a formal evaluation of their approach using a control group. However, they did

present faculty assessments of student performance based on grades of laboratory reports, exams and quizzes. They also demonstrated that an open laboratory format is a better choice in terms of equipment, space and budget constraints.

Another study of an electrical engineering undergraduate open laboratory was conducted by Palais and Javurek (1996) at Arizona State University. Eleven different courses were taught over sixteen weeks in a format that allowed each laboratory to be available for *74* hours weekly. The laboratory was set up in a single large room. This study explored the effect of this format on student attendance. They also adjusted teaching assistant duty hours based on their observations of attendance. They hypothesized that their open laboratory approach would encourage students to become self-directed problem solvers, thereby leading to increased self-confidence and improved learning. They demonstrated that this approach reduced scheduling conflicts and made more efficient use of laboratory space. The overall feedback from students, faculty and administration was positive. They did not, however, conduct any evaluations of student performance or use a control group to assess impact.

Kuhn et al. (2000) combined a traditional lecture with an open laboratory for a senior-level RF design course for Kansas State University. They found that a studio-like setting in their open laboratory enhanced the educational experience through improved interaction among students. Kuhn and his colleagues did not provide any quantitative assessment of their approach. They reported that their approach was effective and enjoyable in terms of student experience. However, no survey data was provided in the paper to support the claim.

The emergence of internet-based technologies has created new opportunities for enhancing the open laboratory experience (Olin et al., 2005). It is a critical piece of any distance learning strategy in engineering. No significant differences can be found in learning outcomes for online and on-campus students as measured by test scores (Bourne & Moore, 2004). These approaches can be classified into two broad categories. The first category of research tried to develop real (physical) laboratories with remote access (Jain et al., 2008; Fjeldy & Shur, 2003). The second category of research attempted to develop fully software-based laboratories (Chaturvedi et al., 2011; Mosterman et al., 1994; Campbell et al., 2002). In our approach, we exploited digital technology to make a physical laboratory portable and consequently accessible from anywhere, anytime. At the same time, we provided a web-based virtual laboratory assistant so that the students receive a self-paced tailored learning environment.

A PILOT STUDY WITH VOLTA

In our open lab approach, we provide students with a portable lab experience through the use of a popular low-cost rapid-prototyping circuit board (Digilent, 2014) equipped with a power supply,

a solderless breadboard, and assorted software-based instrumentation. VOLTA was designed to provide teaching assistance for this hardware. VOLTA was first introduced during the fall semester of 2014 with a basic dialog manager. Students could query the system with questions about definitions, instrument usage, and experimental procedure. The system responded with answers to the queries, which in some cases include video demonstrations.

Based on feedback received from this initial experiment, VOLTA was redesigned for the spring semester of 2015 to include more hardware circuit connection assistance and more example questions. Finally, in the fall semester of 2015, a third version of VOLTA was released with a circuit comparator module that was inspired by the Circuit Recognizer module in the Universal Virtual Laboratory (UVL) (Duarte et al., 2008; Butz et al., 2006; Krishnasamy, 2004). UVL provided a virtual breadboard with miniature instruments (dc power-supplies, a function generator, an oscilloscope, a spectrum analyzer, and a digital multimeter) and electrical components (resistors, capacitors, inductors, diodes, Zener diodes, potentiometers, variable capacitors, transistors, and jumper wires). Students could build a circuit with this virtual breadboard, and compare their implementation to the reference schematic in a lab manual. A Circuit Recognizer module used circuit topology knowledge to verify a student's implementation. This module was written in C++.

In this paper, we created an extension of the Circuit Recognizer module, which we refer to as the Circuit Comparator, in VOLTA. The Circuit Comparator verifies a student's simulated circuit. Students can perform the simulation in one of two popular simulators: CircuitLab (Circuit Lab, 2017) and Multisim (National Instruments, 2017). Circuit Comparator determines the topological equivalence between a student's circuit and a circuit stored in the VOLTA database by comparing netlists (Sandler & Hymowitz, 2006). The circuit comparator described in this paper was developed using Python.

We assessed the effectiveness of VOLTA using a pre-test/post-test methodology (Saleheen et al., 2015; Saleheen et al., 2016) for three types of instructional situations. In the first assessment in Fall 2014, referred to as TA vs. VOLTA LAB 1, both groups received instruction from a human teaching assistant while the experimental group was also given access to VOLTA v1. The control and experimental groups are identified as "Cohort 1". Since the first version of VOLTA was not equipped with all the modules that were planned, we decided to use a human teaching assistant for the experimental group. We found performance was comparable between the control and experimental groups.

The second version of VOLTA, VOLTA v2, was enhanced through the addition of a hardware circuit tracer. The help module also included an enriched Question and Answer (Q&A) database. A second assessment was conducted in Spring 2015 and is referred to as TA vs. VOLTA LAB 2. The control and experimental groups are identified as "Cohort 2". We found that the experimental group performed much better than the control group (Saleheen et al., 2016). These findings were expected since the experimental group received more attention and we exposed the group to more learning opportunities.

For the third assessment of VOLTA, which we refer to as TA vs. VOLTA LAB 3, we reduced the dependency on the human teaching assistant for the experimental group since VOLTA was now fully functional (VOLTA v3). The Fall 2015 control and experimental groups are identified as "Cohort 3". Unlike "Cohort 1" and "Cohort 2" of the previous semesters, the human teaching assistant did not deliver any introductory lectures for the experimental group of Cohort 3. The teaching assistant was present during lab hours for both the control and experimental groups. However, rather than answer questions directly, students were encouraged to find answers using VOLTA. Our assessment demonstrated that the experimental group did not show any difference in learning compared to the control group.

Therefore, the two main research questions addressed in this paper are:

(1) Was there any difference in the performance of the students who used VOLTA (experimental group) and their counterparts in the control group?

(2) Was the student perception of VOLTA positive?

To address the first question, we conducted an effectiveness study on the gain scores found from the pre-tests and post-tests. To address the second question, we ran a usability survey on the students who were taught using VOLTA. The strength of our study is that we evaluated student learning each semester using an ANOVA test. The preliminary evaluation results of VOLTA for the first two semesters have been published in ASEE conferences (Saleheen et al., 2015; Saleheen et al., 2016).

DESIGN AND IMPLEMENTATION

We begin this section by discussing the VOLTA's architecture. This tool was designed to be modular and relatively easy to customize for new lab applications.

The VOLTA Architecture

An overview of the VOLTA architecture is shown in Figure 1. VOLTA is a web-based application and is hosted via a cloud-based server. The students perform lab experiments using Digilent's EE board that includes an instrumentation module. This module includes oscilloscopes, waveform generators, power supplies, voltmeters, reference voltage generators, and thirty-two digital signals that can be configured as a logic analyzer, pattern generator, or any one of several static digital I/O devices. All of these instruments can be connected to circuits built on solderless breadboards using simple jumper wires. For data acquisition and analysis, Digilent's PC-based software, WaveForms™, is used. A high-speed USB 2.0 connection ensures near real-time data acquisition. The EE modules are provided to the students free of charge for the duration of the course.
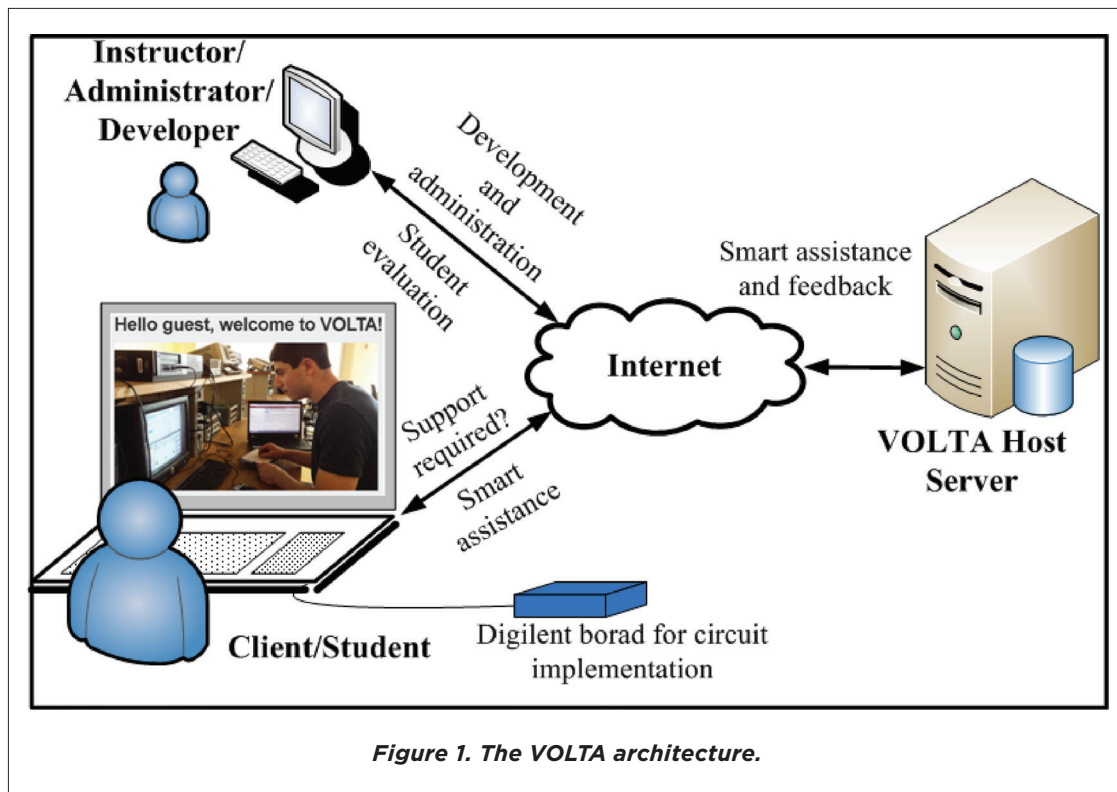
Figure 1. The VOLTA architecture.

VOLTA is preloaded with instructional videos, definitions, and explanations. Therefore, it supports on-demand learning and provides immediate feedback on lab exercises and quizzes. VOLTA also provides an administration panel for instructors for the management of the lab content. VOLTA software consists of four modules and one database. The modules are: (1) Instructor module, (2) Student module, (3) Help module, and (4) Circuit Comparator and tracer module. VOLTA is implemented using Python (version 2.7.1) and Django (version 1.6.5). Django is a high-level Python web framework for rapid and scalable web development (Django, 2014). The details of the modules and implementation can be found in (Saleheen et al., 2016).

Implementation

In Figure 2, we provide an example of the user interface for a typical lab experiment of the course. The center of the page contains the specific lab instructions and relevant resources for that assignment, including theory and simulations. On the left of the page, the learning activities required for completing the experiment are given. These include:

- Theory: describes the theory of the experiment, connecting this experiment with information presented in the lecture section of the course.

Figure 2. The VOLTA user interface.

- Theory Test: administers a multiple-choice pre-test on the theory.
- Simulation: provides instructions for circuit simulation and supports the use of Circuit Comparator to debug and verify simulated circuits.
- Hardware: provides instructions for building a circuit using the EE module with assistance from Circuit Tracer.
- Results: facilitates data collection and analysis, and includes a few questions to probe whether students understand their results.
- Laboratory Test: administers a multiple-choice post-test and assesses performance.

There are three types of general learning resources available to the student. These are linked from the menu bar at the top of the page in Figure 2.

First, FAQ-style videos are provided that contain tutorials on basic electrical concepts, definitions, and lab assignments. Students can submit queries using keywords. The query box is located at the bottom left of the page in Figure 2. These can also be accessed from the Help tab on the menu bar. A screenshot from the help page is shown in Figure 3. Some instructional videos can be found at the start of the course page under the 'Prerequisites' tab. There are instructional videos on how to use breadboards, DC power supplies, multimeters, the Digilent EE module, Waveforms, etc. There is a total of 20 videos, which are also available from a YouTube channel 'Temple Volta' that was created to support the system (see *http://www.temple.edu/csnap/volta.html*).
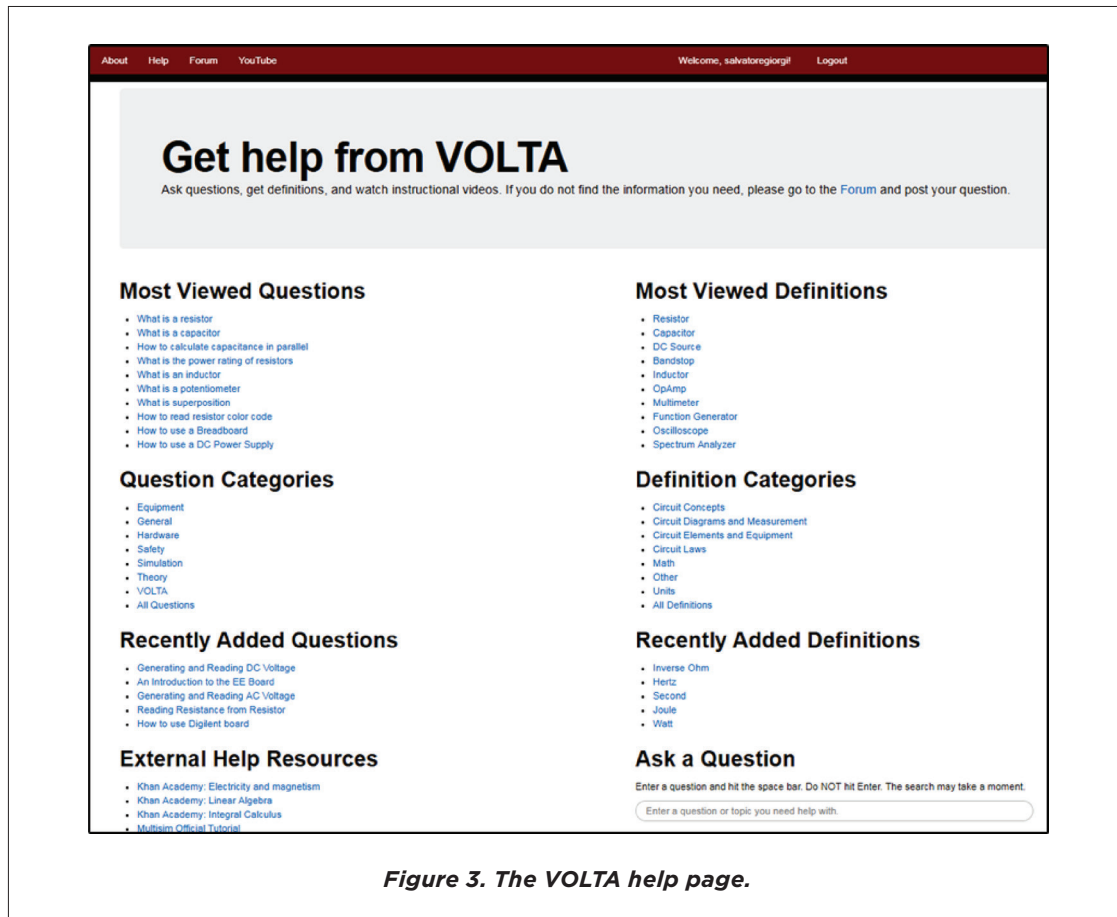
Figure 3. The VOLTA help page.

The second general resource available is Circuit Comparator. Students can compare their circuit to a reference implementation and receive diagnostic information. The objective of the circuit comparator module is to verify whether the students' simulated circuits are equivalent to the reference circuits stored in VOLTA. Figure 4 shows the flowchart of the logic used in Circuit Comparator. This module attempts to emulate the process used by a TA to check the circuit. The steps in the process are described below:

(1) Comments and overhead are removed from student's netlist. Since different SPICE programs generate differently formatted netlists, the circuit comparator uses a netlist translator function. It reads a netlist, checks for component definitions and outputs a simplified netlist. An example is shown in Figure 5 for a Multisim generated 2nd-order RLC circuit with an AC source.

(2) Components are grouped based on their type into arrays, and these arrays are sorted using selection-sorting algorithm (Knuth, 1997). These arrays are compared to the reference implementation by order and value.

Figure 4. A flowchart for Circuit Comparator.

Figure 5. The netlist comparator in Circuit Comparator.
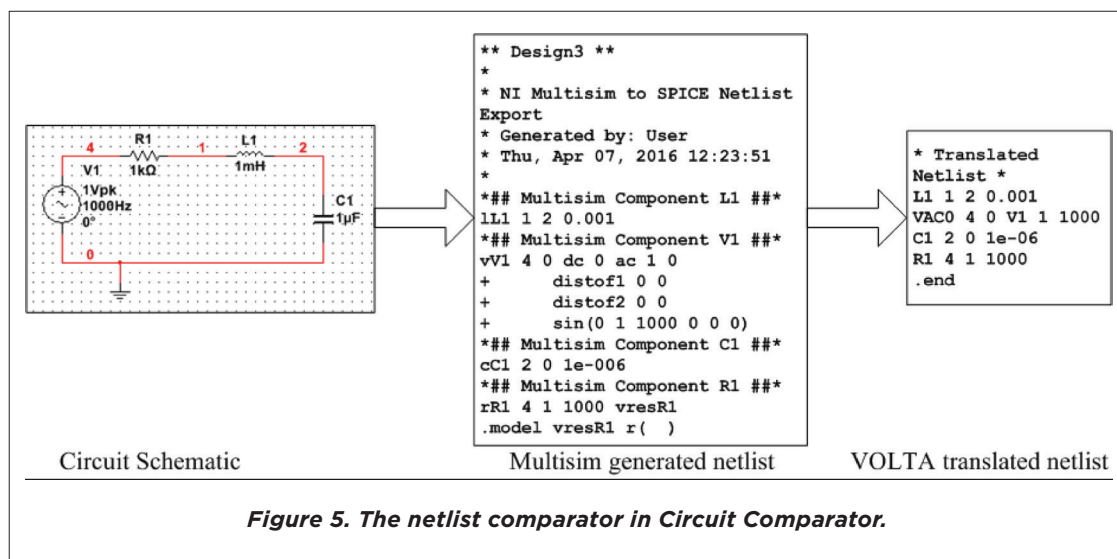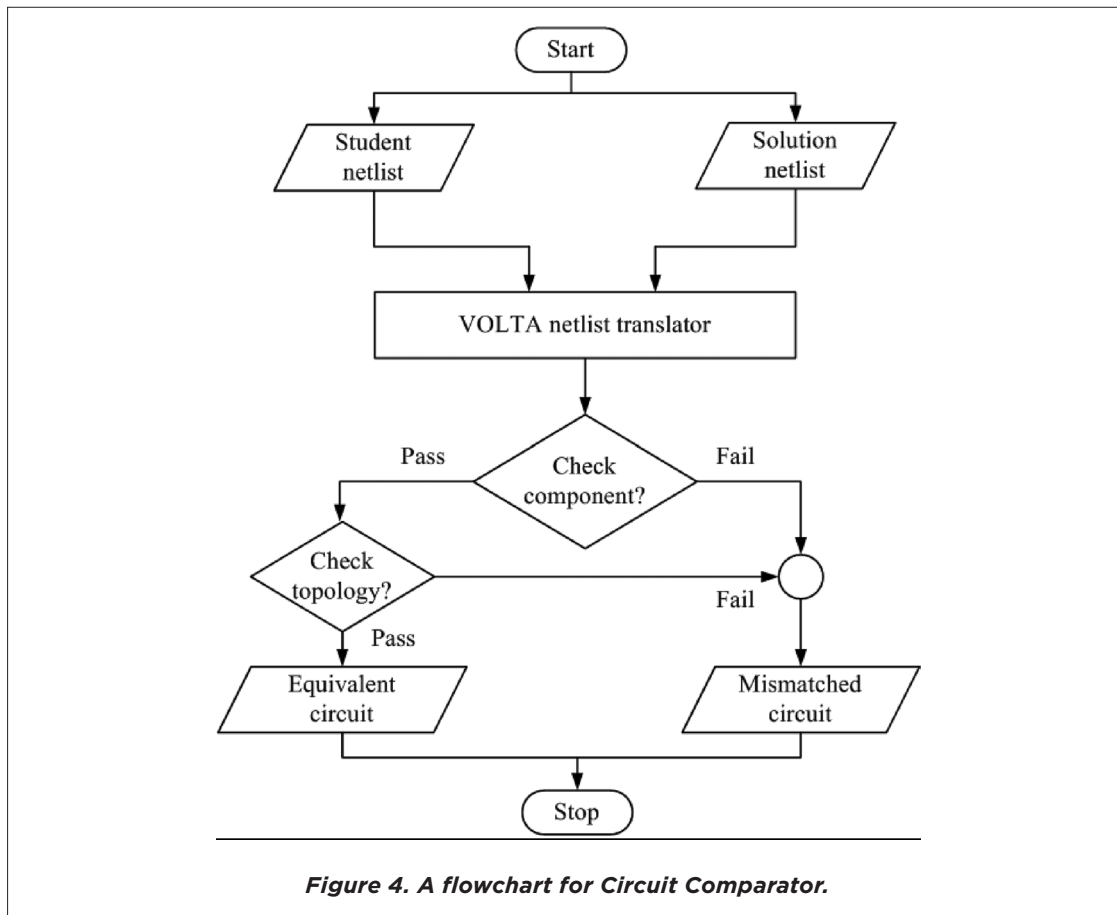
(3) A fundamental loop matrix for the circuit is constructed based on Kirchoff's Voltage Law (KVL). This matrix stores information about the independent circuit loops and components within each loop. The loop matrix is constructed by performing mathematical operations on the basic incidence matrix (Duarte et al., 2005).

(4) The topological equivalence of the two circuits is determined by comparing the loop matrix to the reference circuit. If all the elements and their corresponding values in the loop are identical, the comparator outputs 'equal'. Otherwise, it provides diagnostic information about missing element names and/or incorrect values.

The third general resource available is Circuit Tracer. In this module, students receive step-by-step instruction on how to debug their circuit by tracing circuit connections and performing component integrity tests. Directions on how to use Circuit Tracer can be found inside the learning activity labeled as 'Hardware' on the left panel in Figure 2. An example of Circuit Tracer is shown in Figure 6. Video

Figure 6. An example of Circuit Tracer.

instructions are provided on a range of common topics such as checking for a damaged component and performing a continuity test. Brief descriptions of the circuit topology and node to node connections are provided. A set of videos on these kinds of common implementation problems was developed based on TA feedback.

ASSESSMENT DESIGN

Our goal was to evaluate VOLTA for both effectiveness and usability. The effectiveness study was designed to evaluate the impact on learning compared to traditional instruction. The usability evaluation data provided feedback on the pedagogy as well as the user interface.

Assessment Methods

We used gain score analysis (Brogan & Kutner, 1980; Dimitrov and Rumrill, 2003; Dugard & Todman, 1995) collected from the pre- and post-tests design to evaluate effectiveness. Usability was evaluated using a Likert scale (Ary et al., 2009). The respondents are asked to indicate whether they strongly agree, agree, disagree, strongly disagree, or hold no opinion about the statements. Their responses are assigned numeric values, e.g. strongly disagree = 1, disagree = 2, no opinion = 3, agree = 4, and strongly agree = 5. The mean attitude score was then calculated by averaging the response scores according to the Likert scale. A mean score below 3 shows a negative attitude while a mean above 3 shows a positive attitude.

Our experiment involved eleven topics covered in a second semester electrical circuits course: i) Introduction to Multisim using an RC Circuit, ii) Introduction to the Digilent EE module using RC Circuits, iii) Introduction to First-order Filters, iv) The Step Response of a Second-order Filter, v) The Frequency Response of a Second-order Filter, vi) Design of Second-order Circuit Based on the Step Response, vii) Impedance Measurement in an AC Circuit, viii) Bass Booster Implementation using Active Filters, ix) Gain Bandwidth Product and Slew Rate of an Operational Amplifier, x) Introduction to a Boost Converter, and xi) Introduction to Amplitude Modulation.

Assessment Samples

The study participants were sophomores enrolled in our second semester circuits course for three consecutive semesters: Fall 2014 (Cohort 1), Spring 2015 (Cohort 2), and Fall 2015 (Cohort 3). We evaluated three conditions for each of these cohorts: TA vs. VOLTA LAB 1, TA vs. VOLTA LAB 2, and TA vs. VOLTA LAB 3. In Table 1, we provide the student enrollment data. For Cohort 1, a TA vs. VOLTA LAB 1 experiment was conducted. Both the control (n=18) and experimental (n=16) groups received closed lab TA assistance. The experimental group received additional assistance via VOLTA.

Table 1. Student Enrollment Data.

Period	Cohort	Experiment Type	Control Group	Expt. Group	Total
Fall 2014	1	TA vs. VOLTA LAB 1	18	16	34
Spring 2015	2	TA vs. VOLTA LAB 2	18	10	28
Fall 2015	3	TA vs. VOLTA LAB 3	9	8	17

This version of VOLTA was identified as VOLTA v1, which was equipped with a basic dialog manager. In this dialog manager, students could query VOLTA v1 with questions about definitions, equipment usage, and experimental procedures. The system responded with answers to the queries, which in some cases included video demonstrations.

For Cohort 2, TA vs. VOLTA LAB 2 experiment was conducted. Both control (n=18) and experimental (n=10) groups received closed-lab TA assistance. The experimental group received additional assistance via VOLTA. This version of VOLTA was identified as VOLTA v2, which was a revamped version of VOLTA v1 with "Circuit Tracer" module for hardware circuit connection assistance. A larger Q&A database was introduced in VOLTA v2.

For Cohort 3, a TA vs. VOLTA LAB 3 experiment was conducted. This experiment was slightly different than the previous two experiments since it used a fully-developed version of VOLTA. Therefore, the goal of the experiment was to observe how effectively VOLTA can replace human instruction. In order to achieve the goal, we provided closed-lab TA assistance to the control group (n=9), whereas the experimental group (n=8) received assistance via VOLTA and decreased TA involvement. This version of VOLTA was identified as VOLTA v3, which was redesigned with "Circuit Comparator" module to assist the students for verifying their simulated circuits. The "decreased TA involvement" means during lab hours, the teaching assistant did not answer questions from the students directly, rather encouraged them to find answers using VOLTA v3. Also, in this experiment, the TA did not provide any introductory lectures on lab assignment for the experimental group of Cohort 3.

RESULTS

In this section, we present a statistical analysis of our experiments, including analyses of gain and usability scores.

Gain Score Analysis

A two-group pre-test/post-test design approach was used to evaluate the effectiveness of VOLTA. The major question guiding the evaluation: Is there any difference in the performance of the students

Table 2. ANOVA table for Cohort 1 (Fall 2014).

Source of Variation	Degrees of freedom	Sum of Squares	Mean Square	F ratio	p-value
Lab assignment no.	10	7,654	765.4		
Group	1	705	705	1.878	.1714
Residual	362	135,904	266		
Total	373	144,266			

who used VOLTA (experimental group) and their counterparts in the control group? The gain score is defined as the difference between the post-test and pre-test score. The null hypothesis is that there is no difference among the mean gains of the experimental and control groups for eleven assignments.

For Cohort 1, the ANOVA test (Montgomery, 2007) was performed on the gain scores of 28 students in 11 lab assignments. The ANOVA test was performed using R (version 3.1.2). The ANOVA test revealed that there is no significant effect of VOLTA on the gain scores of Cohort 1, $F(1,10) = 1.878$, $p = .1714$ (Table 2). In other words, there is not sufficient evidence that the students taught with VOLTA performed better than their counterparts in the closed laboratories. The differences are statistically significant at a confidence level of 80%. For Cohort 2, ANOVA was performed on the gain scores of 34 students in 11 lab assignments. The ANOVA test on Cohort 2 gain scores suggested a significant effect of VOLTA on student performance, $F(1,10) = 27.15$, $p < .001$ (Table 3). This indicates there is sufficient evidence that students taught with VOLTA performed better than their counterparts in the closed laboratories. The differences are statistically significant at a confidence level of 95%. For Cohort 3, the ANOVA test was performed on the gain scores of 17 students in 11 lab assignments. The ANOVA test results from Cohort 3, $F(1,10) = 1.878$, $p = .768$, indicated that the null hypothesis cannot be rejected (Table 4). This indicates there is sufficient evidence that there is no difference between the students taught traditionally and taught with VOLTA.

In order to find the strength of the statistical significance of our study, we estimated the effect size qualitatively based on Cohen's d value (Cohen, 2013), as shown in Table 5. We calculated Cohen's d using the following formula (Thalheimer & Cook, 2002):

Table 3. ANOVA table for Cohort 2 (Spring 2015).

Source of Variation	Degrees of freedom	Sum of Squares	Mean Square	F ratio	p-value
Lab assignment no.	10	3,782	378.2		
Group	1	7,215	7,215	27.15	<.001
Residual	296	78,671	266		
Total	307	89,568			

Table 4. ANOVA table for Cohort 3 (Fall 2015).

Source of Variation	Degrees of freedom	Sum of Squares	Mean Square	F ratio	p-value
Lab assignment no.	10	8,766	876.6		
Group	1	29	28.60	.087	.768
Residual	296	78,671	266		
Total	307	89,568			

$$d = \sqrt{F\left(\frac{n_t + n_c}{n_t n_c}\right)\left(\frac{n_t + n_c}{n_t + n_c - 2}\right)} \tag{1}$$

where d is the Cohen's d effect size, F is the F statistic or F ratio, n_t is number of students in the experimental group, and n_c is number of students in the control group. Cohen suggested that d values of 0.2, 0.5, and 0.8 indicate small, medium, and large effects, respectively (Cohen, 1992; Sullivan & Feinn, 2012). For Cohort 1, d was found to be 0.49 for $F(1,33) = 1.878$. The effect size (d = 0.49) indicates that VOLTA had a medium effect. For Cohort 2, d was found to be 2.13 for $F(1,27) = 27.145$. The effect size (d = 2.13) indicates that this is a large effect. For Cohort 3, d was found to be 0.15 for $F(1,16) = 0.087$. The effect size (d = 0.15) indicates that this is a small effect.

The Cohort 1 experiment showed a p-value of .1714 with a medium effect size. From a statistical significance point of view, VOLTA may not introduce much difference in student learning for both groups. However, it showed that VOLTA could perform as good as a TA. Among three cohorts, the Cohort 2 experiment showed evidence with a large statistical significance that the experimental group (VOLTA) learned better than the control group. However, this finding was anticipated since Cohort 2 used an improved version of VOLTA compared to Cohort 1, and a TA was available. Cohort 3 received decreased human assistance. The analysis showed that VOLTA did not make a statistically significant difference in student learning. The effect size turned out to be small for the Cohort 3 experiment.

As for the p-value, note that for Cohort 3 the number of samples were smaller (approximately half) compared to Cohort 1 and 2. As for effect size, note that for Cohort 3 the conditions (the amount of human assistance) changed compared to Cohort 2. Therefore, we noticed a large difference in

Table 5. Summary of p-values results with effect sizes.

Cohort	Experiment type	p-value	Cohen's d	Effect Size
1	TA vs. VOLTA LAB 1	.1714	0.49	Medium
2	TA vs. VOLTA LAB 2	<.001	2.13	Large
3	TA vs. VOLTA LAB 3	.768	0.15	Small

terms of d between Cohort 2 and Cohort 3. Fritz et al. (2012) stated that a small effect size may be very relevant. In our case, the small effect size can be treated as important if we consider whether there is no difference in student learning whether VOLTA or a TA is present.

Descriptive Statistics

We used boxplots (Keen, 2010) to visualize the variance in the pre- and post-test scores. The boxplots in Figure 7 show test score distributions for eleven lab assignments for Cohort 1.

In the pre-tests, the control group has similar median scores of 60 for labs 1, 3, 4, 5, 6, 7, 9, and 10 with a larger variation in labs 1, 3, and 5. In the post-tests, for most of the labs, the median scores increased compared to the pre-tests. There is a larger variability in the scores for labs 3, 5, 6, and 7. The experimental group has median scores of 60 in labs 1, 3, 4, and 10 in the pre-test scores. The post-test score has a larger variation for the experimental group. The control group and the experimental group do not have similar distributions of scores in the pre-tests.

The boxplots in Figure 8 show test score distribution for Cohort 2. In the pre-tests, the control group has a median of 80 in labs 1, 3, 6, 8, and 9, and a median of 60 in labs 4, 7, 10, and 11. Lab 6
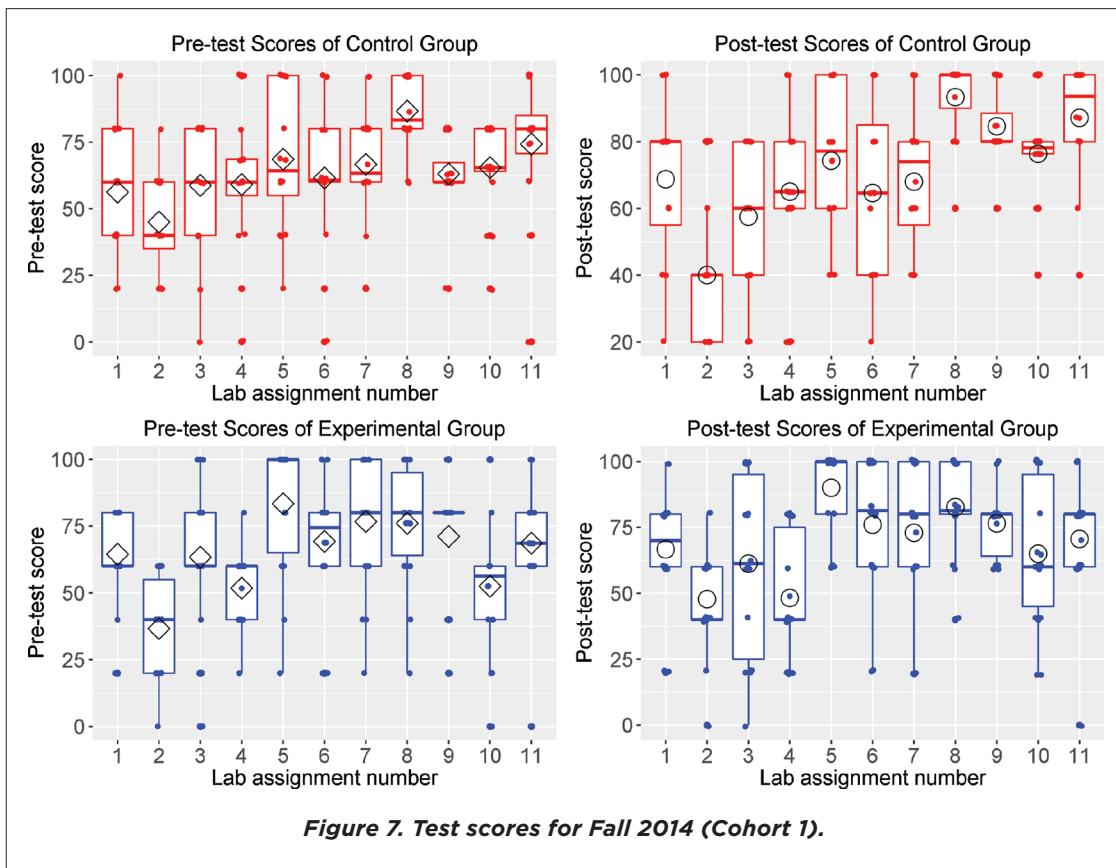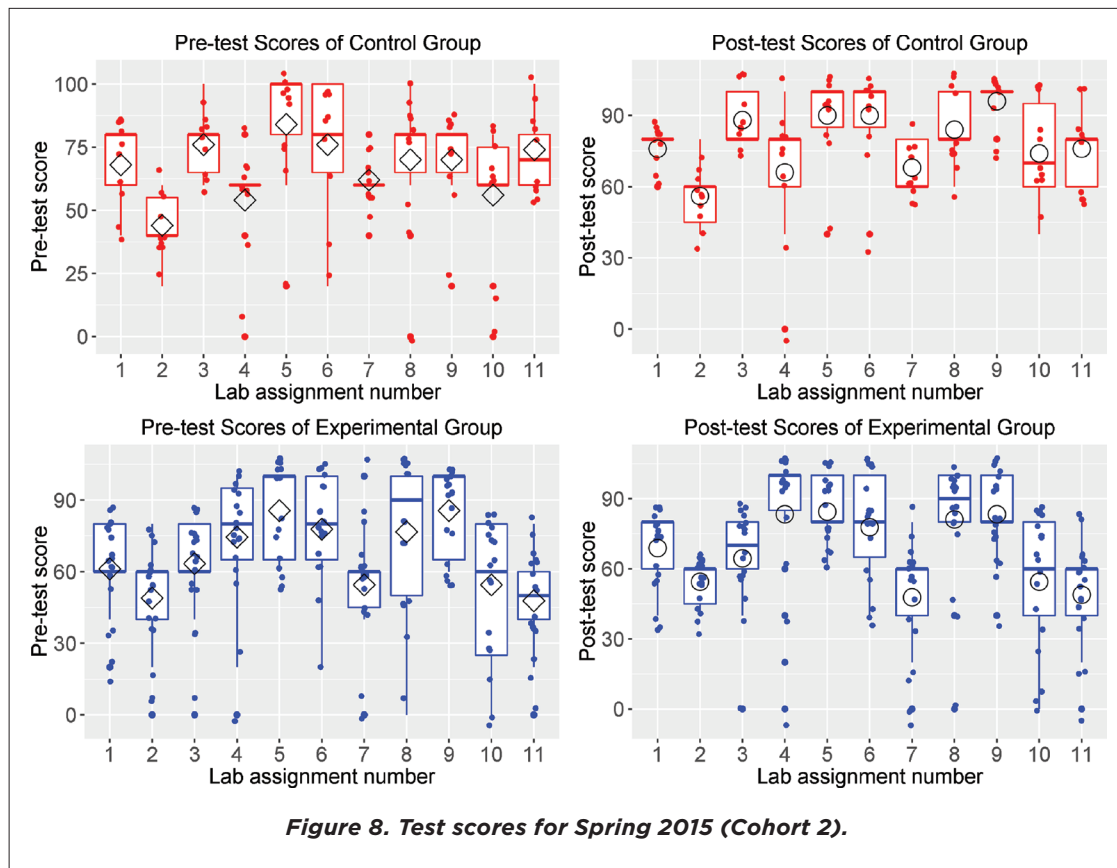

Figure 7. Test scores for Fall 2014 (Cohort 1).

Figure 8. Test scores for Spring 2015 (Cohort 2).

showed a larger variation. In the pre-test, the experimental group has a median of 80 in labs 4 and 6, and a median of 60 in labs 1, 2, 3, 6, 7, and 10. The experimental group has a larger variation in labs 8 and 10. The control group pre-test scores were slightly higher than the experimental group in terms of medians. In the post-tests, the experimental group median scores increased and the variation becomes smaller compared to their pre-test performance. The control group did not show any significant changes in the post-tests compared to the pre-tests.

The boxplots in Figure 9 show the test score distributions for Cohort 3. In the pre-tests, the control group has a median of 80 in labs 1, 3, 5, 9, and 11, and a median of 60 in labs 2, 4, 7, 8, and 10. Labs 1, 6, 7, 9, and 10 showed a larger variation. In the pre-test, the experimental group has a median of 80 or more in labs 3, 5, 7, 8, 10, and 11 and a median of 60 in labs 2, 4, and 6. The experimental group has larger a variation in labs 5 and 6. The control group pre-test scores were slightly higher than the experimental group in terms of medians. In the pre-tests and post-tests, the experimental group has less variation than the control group.

The boxplots in Figure 10 – Figure 12 show the gain score distributions for each of the cohorts. For Cohort 1, the control group has a larger number of negative gain scores compared to the experimental

Figure 9. Test scores for Fall 2015 (Cohort 3).
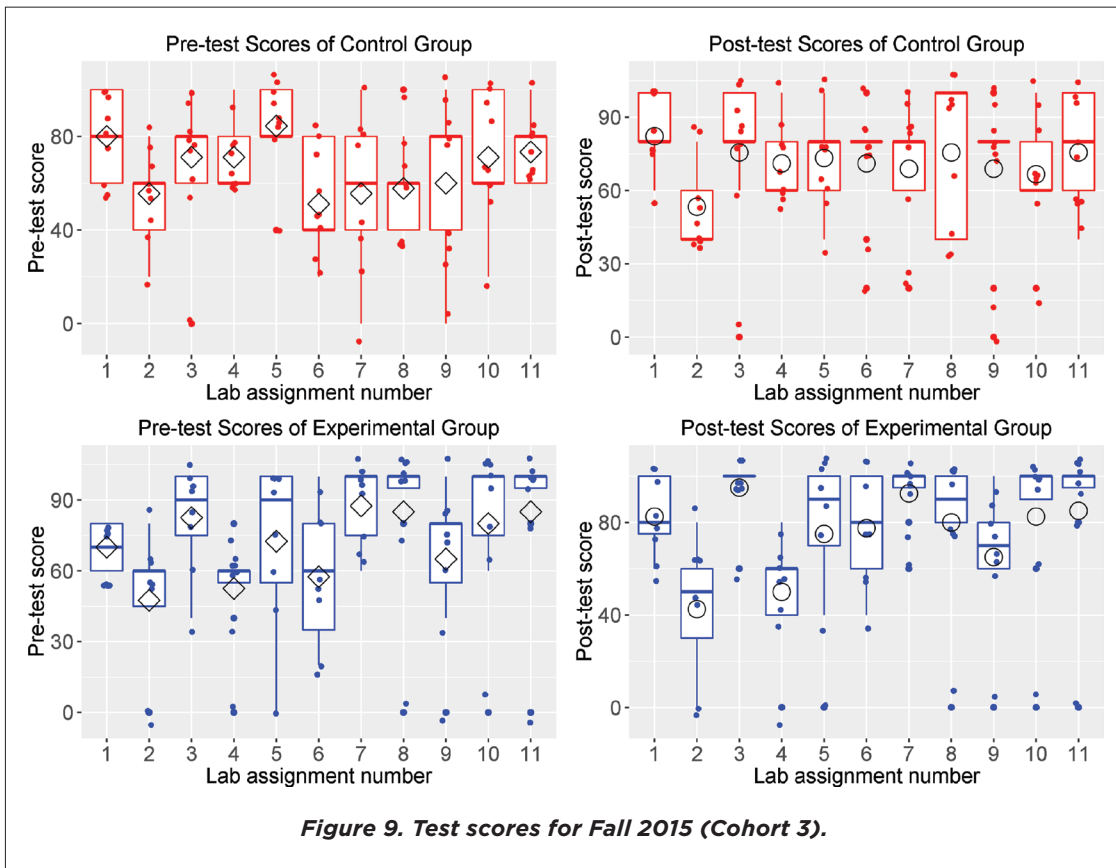
group. Similar trends can be observed for Cohort 2. For Cohort 3, both control and experimental groups showed a similar distribution of gain scores.

From the average gain plot in Figure 13, we observe that the experimental group performed better in lab assignments 1, 7, 9, and 11, whereas the control group did better in lab assignments 2 and 6 for Cohort 1. The rest of the lab assignments showed little difference. In terms of average gain, the experimental group performed better than the control group for Cohort 2. The difference between the control and experimental group is not significant for Cohort 3.

Usability Survey Analysis

The usability evaluation is based on a survey response of six students (out of eight participants) in Cohort 3. In this study, twenty questions were asked covering seven broad categories. Table 6 lists the usability survey questions. We prepared these usability survey questions based on the usability survey questions used to evaluate Interactive Multimedia Intelligent Tutoring System (IMITS), developed under Science, Engineering and Educator Intelligent Tutor (SEE-IT) project, funded by National Science Foundation (grant number DUE #9952291) (Butz, 2003).

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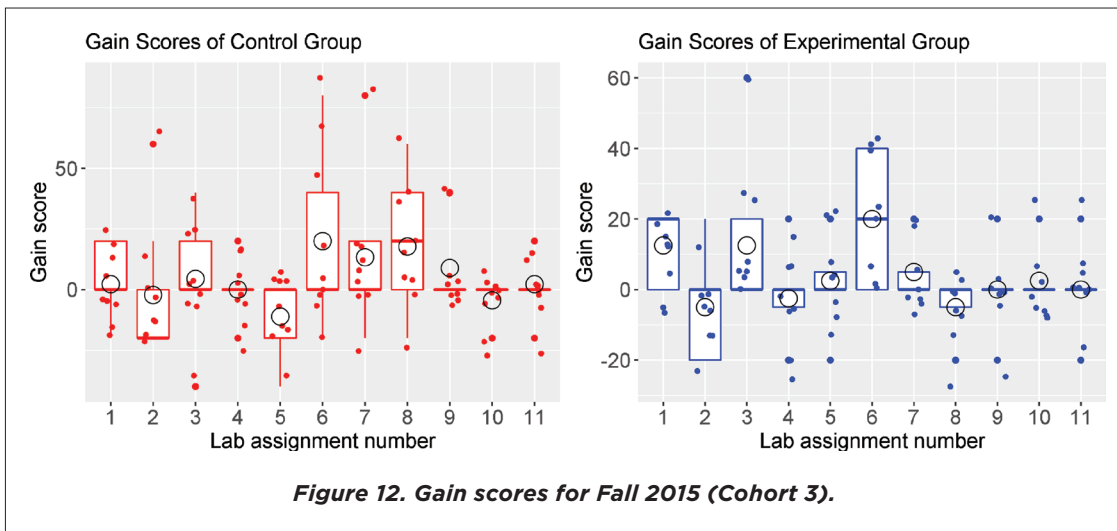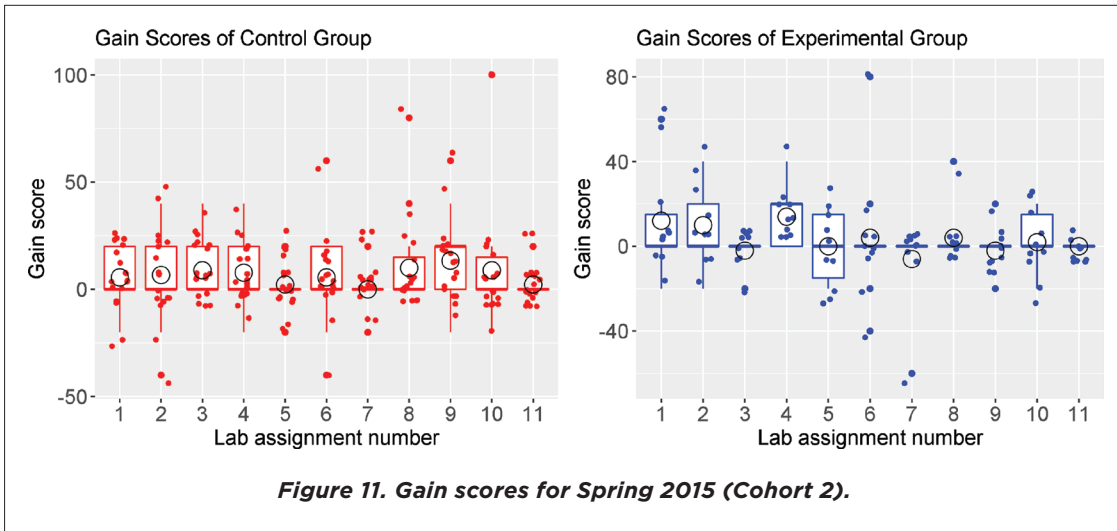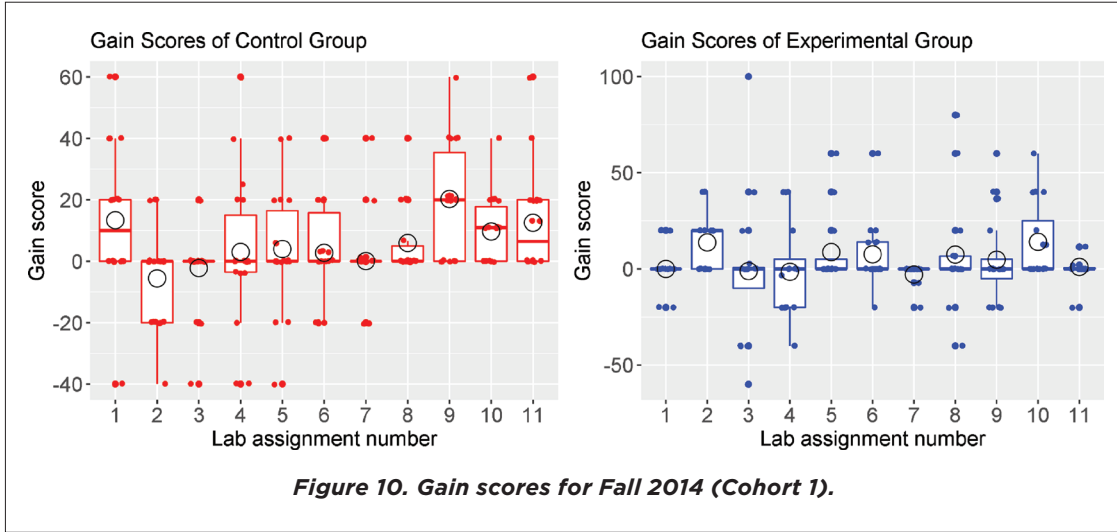## for Electric Circuits

Figure 10. Gain scores for Fall 2014 (Cohort 1).

Figure 11. Gain scores for Spring 2015 (Cohort 2).

Figure 12. Gain scores for Fall 2015 (Cohort 3).

Table 6. Usability survey questions.

Category	Objective	Survey Questions
A. Learning environment	Did the students think VOLTA was useful for their learning?	A1. VOLTA helped me to learn electrical circuits' concepts. A2. I felt I could trust the VOLTA to properly inform me. A3. The longer I spent using the VOLTA, the more information I felt I retained. A4. I needed to respond quickly to the assignment questions. A5. The simulation tests helped me understanding the concepts.
B. Motivational value	Did the students find the software motivating?	B1. I enjoyed using VOLTA. B2. I lost track of time while using VOLTA.
C. Ease of use	Did the students find VOLTA easy to use?	C1. VOLTA was easy to use. C2. The use of VOLTA was intuitive. C3. I was able to navigate within the sections of labs easily.
D. Perception of usefulness	Did the students perceive the usefulness of VOLTA features?	D1. The 'HELP' module of VOLTA was helpful. D2. The 'YouTube channel' of VOLTA showed helpful demonstrations. D3. I used 'Forum' for interacting with students and instructors for solving my problem. D4. VOLTA helped me verify the lab results.
E. Authenticity of virtual learning	Did the students trust the virtual laboratory environment?	E1. The interaction with the VOLTA was personal and I felt as though the teaching assistant was helping me directly. E2. The lab seemed or "felt" like a real lab.
F. Quality assurance	What was the perceived quality of VOLTA?	F1. The videos were of good quality. F2. VOLTA ran trouble-free.
G. Expectations	What additional features the students would like to see in VOLTA?	G1. Would a virtual troubleshooter for the circuit in VOLTA be useful? G2. Would you like to be able to ask the teaching assistant questions from within the VOLTA and have him/her respond?

Table 7 shows the Likert scores found from the survey conducted on the Cohort 3 experimental group. For the category A questions (learning environment), *50%* of the students rated VOLTA as a useful learning tool in terms of concept acquisition based on the responses to questions A1 and A5. The response for question A4 demonstrated that *50%* of the students thought that the pace of the lab was comfortable and they were not forced to hurry through the lab – a common complaint for closed-lab instruction.

Table 7. Likert scores of survey respondents from the Cohort 3 experimental group.

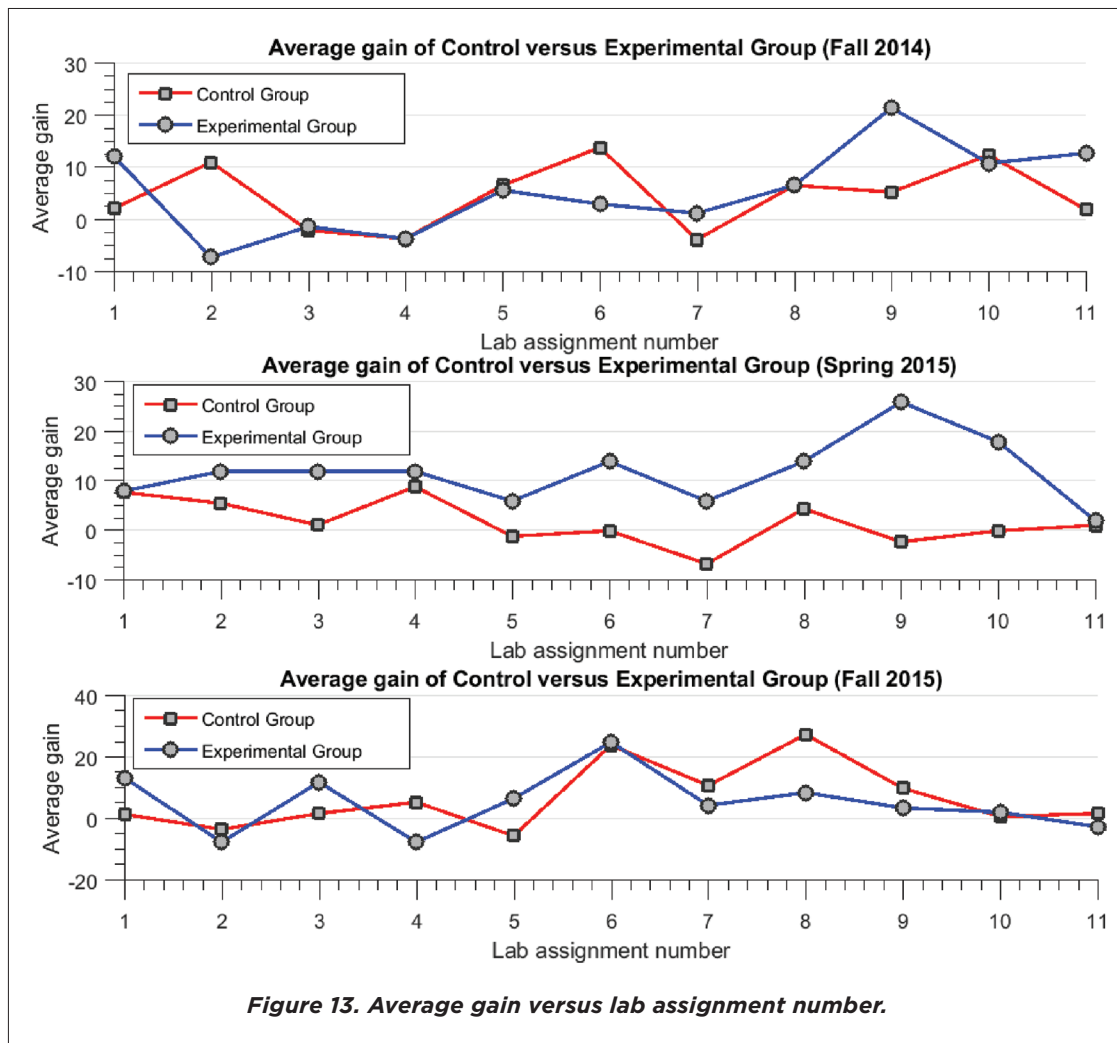| Category	A	A	A	A	A	B	B	C	C	C	D	D	D	D	E	E	F	F	G	G
Question No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
R1	3	3	2	3	2	3	3	4	2	4	1	3	2	3	2	4	3	4	4	4
R2	4	2	3	4	4	4	2	4	3	5	1	3	1	4	3	5	4	3	5	5
R3	2	4	2	2	4	2	2	4	4	4	2	2	2	2	2	2	2	2	4	4
R4	1	1	1	2	2	1	2	1	1	1	1	1	2	2	2	1	1	1	1	2
R5	4	2	4	2	5	2	3	5	4	5	3	5	3	3	2	2	5	5	5	3
R6	4	2	4	4	3	4	2	5	5	4	3	3	3	4	1	4	3	2	4	5

Figure 13. Average gain versus lab assignment number.

According to the responses of category B questions (motivational value), more than 50% of the students did not enjoy VOLTA. One possible reason they did not like VOLTA is that they see it simply as additional work. Note that Cohort 3 students did not receive assistance troubleshooting their circuits from the TA, since the TA was instructed to direct the students to use VOLTA. The responses to question B indicated a moderate level of engagement.

The responses from the category C questions (ease of use) show that 83% of the students found VOLTA easy to use and easy to navigate. 50% of the students also felt that the use of VOLTA was intuitive.

The responses from the category D questions (ease of use) show that student endorsement varied for different features of VOLTA. Most of the students did not find help module to be helpful. A possible reason may be that they needed to navigate more than one page to obtain an answer.

At least one-third of the students gave "no opinion" responses in all the questions in the category. 16% of the students thought the VOLTA YouTube channel was useful.

The responses for question E1 shows that few students thought VOLTA was as helpful as a TA. However, 50% of the students felt that the labs seemed like a real lab based on the responses from category E. For both questions, 33% of the students agreed the videos were of good quality and VOLTA was trouble-free based on the responses from category F. Most of the students indicated that they would like to have a troubleshooter in VOLTA and a way of communicating with a human through VOLTA based on the responses from category G.

For Cohort 1, all 16 students in the experimental group participated in the survey. For Cohort 2, 7 out of 10 students took the survey. For Cohort 3, 6 out of 7 students participated. Figure 14 – Figure 16 show the histograms of the mean attitude scores of the respondents. The left histogram in each plot shows the respondent attitude score, while the right histogram shows the category attitude score. The plots of histograms also include error bars and a horizontal line showing the location of a mean attitude score of 3.

Figure 14 demonstrates that 13 of 16 respondents from Cohort 1 showed a positive attitude (mean attitude score > 3). Since all the category responses were positive, these results demonstrated that the students appreciated VOLTA v1 as a learning tool when augmented with TA help. Figure 15 shows that all *7* respondents showed a positive attitude towards VOLTA. The positive attitude was also observed in category attitude scores. Note that the Cohort 2 experimental group received a similar treatment as their counterparts in Cohort 1 except that VOLTA v2 was enriched with more Q&A and Circuit Tracer.
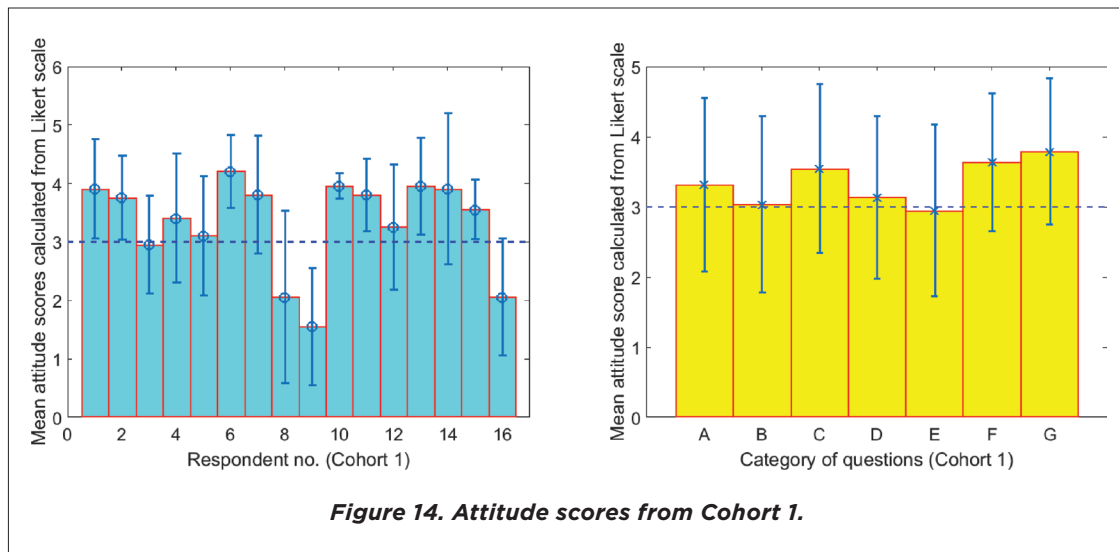

Figure 14. Attitude scores from Cohort 1.
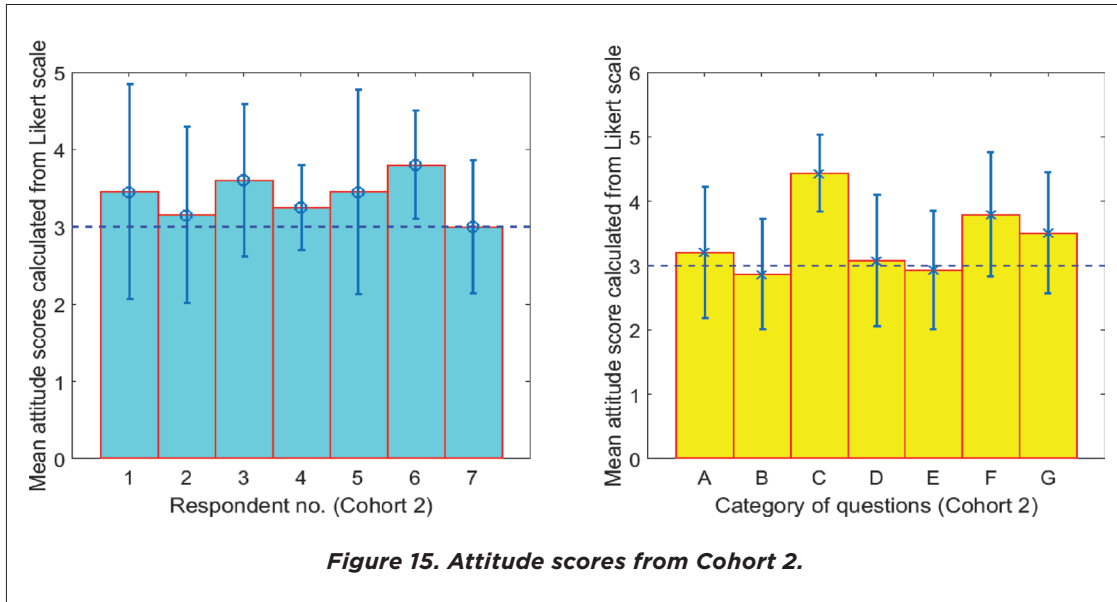
Figure 15. Attitude scores from Cohort 2.

Figure 16 demonstrates that 3 of 6 respondents indicated a positive attitude towards VOLTA. The histogram on the right of Figure 16 demonstrates that, with the exception of category C and G, the mean attitude score of the students fell below 3. These results suggest that the majority of students did not appreciate VOLTA v3 when there was decreased TA involvement, though this is a very small sample size. VOLTA did, however, receive positive attitude score from the students when offered in addition to TA assistance.

Figure 16. Attitude scores from Cohort 3.
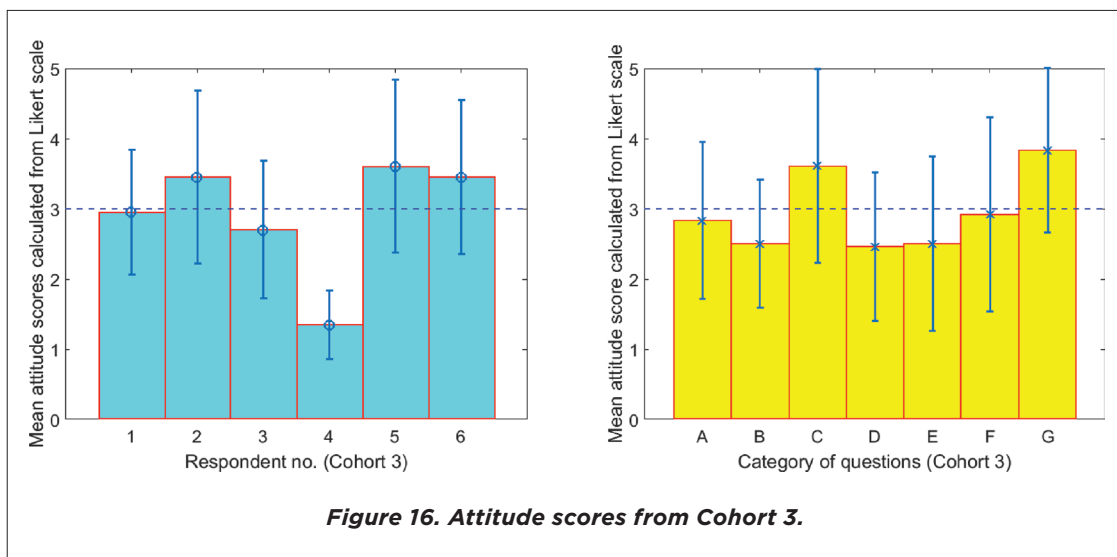
CONCLUSIONS

VOLTA is an intelligent tutoring system with virtual teaching assistance. It was designed to support students in an open laboratory environment. An improved version of virtual teaching assistant was developed with important new features such as a dialog manager, Circuit Comparator and Circuit Tracer. We assessed both the effectiveness and usability for three cohorts of students in an undergraduate electric circuits laboratory.

One of the major research questions of this study was "Is there any difference in the performance of the students who used VOLTA?" The ANOVA test result for Cohort 1 suggested that students in the experimental groups performed similarly compared to their counterparts in the control group with a medium effect. For Cohort 2, the ANOVA results suggested that students in the experimental group performed better than their counterparts in the control group. For Cohort 3, the ANOVA results suggested there was no difference in learning outcomes between the closed and open laboratories. This suggests that VOLTA is as effective as a TA in guiding the students through laboratories, and therefore is a useful learning tool.

The usability results were equally promising. The experimental groups of Cohort 1 and 2 showed a positive attitude towards VOLTA. However, the survey analysis from Cohort 3 revealed mixed results in terms of a positive attitude towards VOLTA. Note that Cohort 3 received decreased TA involvement. It is not surprising that some students might prefer human assistance, since they were not asked to consider the associated costs of human instruction as part of the decision-making process. Additionally, only *6* out of *8* students from the Cohort 3 experimental group took the survey, which is not a sufficiently large sample. (In the future, we plan to offer greater incentives for participation.)

VOLTA was designed to be extensible and can be easily applied to other engineering laboratories involving electronics, communications, and control systems. A certain amount of laboratory material development is needed, but the general structure can be reused. Since the hardware we used for this lab is extremely portable, VOLTA is an excellent platform to support students taking online courses and can solve many challenges associated with offering laboratories for Massive open online courses (MOOCs).

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