

# Teaching Battery Basics in Laboratories: Hands-On Versus Simulated Experiments

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**Abstract—Contribution:** Prior studies comparing the effectiveness of different laboratory learning modes do not allow one to draw a universally valid conclusion, as other influences are mixed with the learning modes. In order to contribute to the existing body of work and to add another piece to the puzzle, this article demonstrates an improved methodology to evaluate the effectiveness of computer-simulated laboratories in comparison to hands-on exercises using a battery basics practical course as a case study.

**Background:** Computer-simulated experiments are becoming increasingly popular for conducting laboratory exercises in higher education and vocational training institutions. To ensure the consistent quality of laboratory learning, an accurate comparison between the results of simulated experiments and practical hands-on experiments is required.

**Intended Outcomes:** In this article, the achievement of the following learning objectives were compared between the two laboratory modes: 1) comprehension of the most important parameters of battery cells and 2) knowledge on how these parameters can be determined using adequate experimental procedures.

**Application Design:** To avoid interference of factors other than laboratory mode on the learning, laboratory instructions and experimental interfaces ensured identical execution of the experiments in the compared modes. Using a counterbalanced methodology, the two laboratory modes alternated by the session, while the experimental procedures remained constant regardless of the respective modes.

**Findings:** Tests taken by the participants after conducting the laboratory experiments revealed that hands-on laboratories resulted in statistically significantly better student performance than simulated laboratories. This difference was even more pronounced for the participants that finished a vocational education and training program before the university studies.

**Index Terms—**Battery, electrical engineering, energy storages, hands-on, knowledge gain, laboratory learning, simulation, student experience.

## I. INTRODUCTION

TO ACHIEVE an optimum student learning and to develop valuable skills for future employment, engineering courses often complement lectures and tutorials with laboratory classes [1]–[3]. This study was designed to discover whether there is any difference between the results of hands-on laboratories and the results of simulated laboratories when other influencing factors are held constant.

The linkage of the theoretical learning with laboratory experiments is particularly relevant at German universities of applied sciences, which attach great importance to the practice-guided learning [4]. The equipment for hands-on laboratory experiments as well as laboratory supervision of classes that require physical equipment can be costly [5], especially when dealing with potentially dangerous materials such as lithium-ion battery cells [6]. Therefore, hands-on laboratories are often replaced by computer-based learning through simulated experiments. To avoid a deterioration in learning quality, it is necessary to compare the effectiveness of simulated laboratory experiments with the effectiveness of hands-on laboratory experiments.

A recent trend toward the virtual and remote laboratories can be seen in publications on laboratory learning [7]. Most studies that investigated knowledge and understanding gained as a result of laboratory work concluded that student learning was either improved or stayed the same when hands-on laboratories are replaced by computer-based laboratories [8].

Most often, participants from experimental and control groups learned under considerably different conditions [9], [10]. Some scholars did not regard different learning modes as directly rivaling solutions for the same educational objectives, but instead tried to achieve different study goals, thus developing and optimizing each mode independently [9], [11]–[16].

Scholars who compared the educational effect of different laboratory modes often omitted other important influences on student learning. For example, Mathiowetz *et al.* compared the results of an online anatomy software-based pathology investigation with a gross anatomy laboratory. The hands-on laboratory group had a significantly higher grade percentage

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and showed more self-perceived learning and higher satisfaction with the laboratory than the online software-based group [17]. This outcome, however, cannot be generalized due to the significant differences in student laboratory experiences: students were permitted to select their preferred learning mode and the time students spent in the gross laboratory differed from the time that was devoted to the software-based laboratory.

An investigation conducted by Sarabando *et al.* targeted an improvement in the student understanding of weight and mass. The researchers discovered that students involved in simulation-based learning performed better than their peers who participated in either a mix of simulation and hands-on or only hands-on learning [18]. Unfortunately, these results cannot be generalized either. First, different teachers taught classes utilizing different laboratory modes. Second, students who learned with simulations had more aspects of weight and mass to reflect upon than their peers who engaged in the hands-on mode (e.g., weight and mass on the moon). Using simulations to enrich lessons with contents difficult to demonstrate otherwise, Stern *et al.* [19] reported improved results of seventh graders regarding the understanding of the kinetic molecular theory in contrast to the hands-on lab.

In their literature review on the comparison of different modes of laboratory work, Ma and Nickerson [9] concluded that the reviewed studies do not allow to draw a universally valid conclusion on the superiority of any laboratory mode. Since the change of modes is associated with other factors influencing the learning, these studies benchmarked a mix of all aspects. Examples for such factors are adapted learning objectives and tests, scope and type of supervision, distance learning versus learning at university, customized experimental approach or synchronous/asynchronous learning, and different teaching materials. Thus, the majority of studies do not allow to pinpoint the effectiveness of learning to one influencing factor [10], which also applies to the influence of the learning mode. This may explain the uncertainty in the findings of recent reviews examining the laboratory learning [8], [9].

To establish more reliable and generalizable insights into the influence of a certain laboratory mode on learning, this study aimed to exclude other influencing factors with the exception of the learning mode itself. Using a counterbalanced within-subject methodology, the laboratory modes alternated, while the learning objectives and the experimental approach of laboratory exercises remained practically identical. The more universal insights derived by the proposed methodology could help engineering educators to offer students laboratory experiments in the most effective mode.

#### A. Modes of Laboratory Experiments

The laboratory experiments can be categorized depending on the *type of access* (local versus remote) or the *resource* (physical versus simulated or virtual). A locally conducted laboratory that uses physical equipment is known as traditional or hands-on. Remote virtual, remote physical, and local virtual laboratories are categorized as nontraditional and represent three other combinations of laboratory modes [7].

This article presents the outcome of a study that was carried out in a *local* access domain. It compares the test results of a hands-on laboratory with that of a virtual laboratory (simulated on a local computer). The main research question of this study was to establish whether there is any difference between the test results of students who participate in hands-on laboratories to students who participate in simulated laboratories. All other factors were held constant to minimize differences between sessions in both modes. Thus, even when there was a possibility to shape the curriculum according to the learning modes (for instance, a time lapse with simulations or adding different aspects about connecting the cells during hands-on experiments), the content and experimental procedures were not altered. Having to select between experimental procedures that fit only one learning mode or procedures that can be taught similarly in both learning modes, the latter approach was chosen. Thus, this article does not determine which of the modes is better for teaching batteries specifically, but the influence of the laboratory modes on student learning in general. Since the study at hand focuses on a strict methodological approach, a *remote* laboratory condition could not be included, even though many students favor online education and recent literature reports equal or better learning with remote laboratories [7], [8], [20]–[22]. The study was designed to compare in-person laboratory teaching with/without proper laboratory equipment solely in the *local* domain.

#### B. Interaction With Equipment

Interaction with equipment can vary depending on the laboratory mode and can require different sets of skills. *Interactive* experiments are those in which students monitor and control some aspects of the experiment during its execution. With *batched* experiments, the sequence and the parameters of the experiment are specified before the experiment begins and the results become available after the experiment ends. *Sensor* experiments are also planned but offer participants an opportunity to follow live data, although they are not allowed to control any aspect of the running experiment [23]. In this study, three out of four content areas of laboratory exercises were designed as *sensor* experiments. During laboratory exercises devoted to the fourth content area, students were given an opportunity to control some aspects of the experimental procedure. The duration of laboratory experiments differed based on content. Determining the dc internal resistance of a battery, for example, only took minutes to complete, while some exercises that required battery discharge took more than 1 h to finish. Durations of hands-on and simulated experiments were practically the same.

## II. METHOD

In order to minimize the influence of various study factors on knowledge acquisition as a result of conducting hands-on and simulated laboratories, a methodology similar to a crossover trial in medicine was applied. Subjects receive a sequence of different treatments. For example, in the first phase of a study, participants of one group receive treatment

TABLE I  
STUDY RUNS

Study Run	Year	Content		Language/ Location	Lab. time /h
		Areas	Language/ Location		
R1 Electric Mobility (B. Eng.)	2016	4	Ger.	THI	14
R2 Electric Mobility (B. Eng.)	2017	4	Ger.	THI	14
R3 International Summer School	2017	2	Eng.	THI	4
R4 IEEE guest laboratory	2017	2	Eng.	TUC	4
R5 Renew. Energy Sys. (M. Sc.)	2017	2	Eng.	THI	4

THI = Technische Hochschule Ingolstadt

TUC = Technische Universität Chemnitz

Ger. = German Eng. = English

A and participants of the other group receive treatment B. In the second phase, treatment B is administered to the subjects of the former group, while treatment A is administered to the subjects of the latter group [24].

In order to implement a similar methodology in this study, participants were divided into two comparable groups. Both groups had the same learning objectives which were clustered around either two or four content areas depending on the study run as shown in Tables I and II. Each group was divided into teams of three to five students to conduct laboratory experiments together. Every student group worked on content areas in the same order but switched the laboratory mode between sessions. The first group conducted simulated experiments in odd weeks of the semester while the second group conducted hands-on experiments. During even weeks of the semester, the groups switched their respective modes: the first group was involved in hands-on experiments and the second group in simulated experiments. Thus, in contrast to medical crossover studies, participants in this counterbalanced within-subject study were not exposed to both learning modes with the same learning objectives. Each week before the laboratory, students were notified of the mode they will conduct the laboratory in.

To assess the influence of a learning mode on knowledge acquisition during a laboratory, a 10-min test was held at the beginning of each subsequent laboratory session.

As shown in Tables I and II, this study was conducted over two years (2016 and 2017) in five study runs (R1–R5). Two runs were conducted in German with second year electric mobility bachelor students, and the other three were conducted in English with students of mixed background. In total, 129 students participated in the study. All students were asked to join this fully anonymous study, and all agreed to participate. Participants did not receive any incentives for taking part in the study, monetary or otherwise.

#### A. Learning Objectives and Content Areas

The laboratory program followed the main learning objectives that aimed to provide students with a sound understanding of energy storage systems. Upon completion of the course, students were expected to comprehend the most important parameters (e.g., internal resistance and open-circuit voltage) and the characteristic behavior (e.g., temperature dependencies of parameters) of battery cells. They should have also determined these parameters independently through suitable experimental setups. The students were expected to comprehend the effects when connecting battery cells to build energy

storage systems. Emphasis was laid on the design of cell type-independent experiments, as cell types are expected to change over a student's career as an engineer.

Laboratory experiments covered four content areas: (A) contact and isolation resistance; (B) open-circuit voltage; (C) internal resistance and power; and (D) energy of cells [25].

Within these areas, seven laboratory experiments in both modes were developed: (A1) *Low Resistance Measurements*: on procedures for low ohmic measurements (Kelvin measurement); (A2) *Contact Resistance*: experiments with a variety of typical electrical connections in battery systems to determine exemplary contact resistance values; (A3) *Isolation Resistance/Flash-Over Voltage*: handling appropriate measuring equipment to determine insulation resistance; (B) *Voltage of Lithium-Ion Cells*: the dependence of voltage on the state of charge using two different types of cells; (C1) *Internal Resistance*: the influence of internal resistance on the efficiency of a battery system (covering ac- and dc-methods to measure internal resistances including the temperature dependence as well as applying industry standards like ISO 12405-1); (C2) *Power*: the maximum discharge rate of battery cells (covering dependency of the maximum discharge power on the state of charge, pulse duration, and temperature); (D) *Energy and Capacity*: the capacity of lithium-ion cells and factors influencing capacity (including calculating the efficiency of charge and discharge cycles).

#### B. Design of Teaching Experiments and Instructions

Each laboratory experiment was developed to cover both modes. The measurements during simulations and hands-on experiments were displayed on the computer screen as graphs and numerical values. Students that took hands-on exercises used physical equipment that also displayed the momentary values of current and voltage. All the experimental procedures were created so that each individual step (e.g., starting a discharge current of 1 A for 2 s, followed by a rest phase to record the voltage response) was the same in both modes, independent of the usage of simulation or hands-on equipment. Since Chamberlain *et al.* [26] discovered that the intensity of guidance can strongly influence the students' research activities, only a single set of written instructions was used in both modes. The instructions included preliminary questions, guidelines for the experiments, and advice on the analysis and collection of data.

To facilitate critical thinking and to reduce the influence of teacher supervision, all experiments were designed to allow students to execute tasks independently in a supervised environment. All the learning objectives could be met by following the set instructions without further help from the instructor. Moreover, the laboratory instructions explicitly encouraged learning through trial and error.

Students who participated in one of the two study runs in German (R1 and R2) conducted five laboratory experiments that covered all the four content areas (content area C was covered over the course of two sessions). The laboratory experiments took 2 h and 50 min each. After the completion of all laboratory experiments, students used their actual laboratory

TABLE II  
 PARTICIPANTS OF THE STUDY RUNS

Study Run	Students	Amount of Practical Experience (I.D.1)		Female	Background	Age / Years		Semester of Studies
		M	SD			M	SD	
R1 Electric Mobility (B. Eng.) 2016	40	0.49	0.33	5%	German	23.3	2.2	4
R2 Electric Mobility (B. Eng.) 2017	30	0.44	0.57	13%	German	23.4	2.5	4
R3 International Summer School	32	n/a	n/a	12%	International	23.4	3.0	3-9
R4 IEEE guest laboratory	9	n/a	n/a	n/a	International	n/a	n/a	n/a
R5 Renewable Energy Systems (M. Sc.)	18	-0.08	0.49	<20%	International	25.8	2.4	8
All Study Runs	129			<25%				

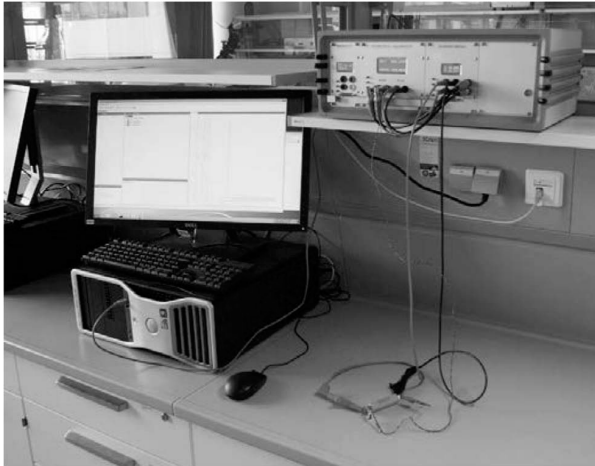


Fig. 1. Hands-on laboratory setting: hands-on battery testing device (upper right) and example cell (bottom right) without thermostat. The computer is executing the graphical user interface.

measurements in a workshop to parameterize a battery simulation model. All the necessary basic theoretical knowledge was gained from a lecture course on battery systems that was conducted in the same semester (4 h per week). During the study runs in German, participants were asked to prepare a written laboratory report for each content area prior to the following session. Submission of all laboratory reports was required to be admitted to the final examination (written) of the lecture course.

Shortened English versions of the laboratory experiments were designed for participants of the summer school (R3), the guest laboratory trial (R4), and the master's degree program (R5). These shortened versions covered two content areas ( $B^*$  and  $C^*$ ) and took approximately 2 h each. As preparation for these experiments, participants received a short introduction to lithium-ion cells.

Instructions were provided to all the study participants of each study run as a group in order to minimize the influence of prior knowledge of individual students on the effectiveness of laboratory learning. All laboratories were supervised by the same instructor.

To validate the laboratory experiments before starting the main study, the experiments were piloted with students of a part-time master program in 2016.

During the main study, each session was conducted as follows. After meeting at the laboratory room (hands-on experiments) or at the computer lab (simulated laboratories), the experiment of that session was introduced and students

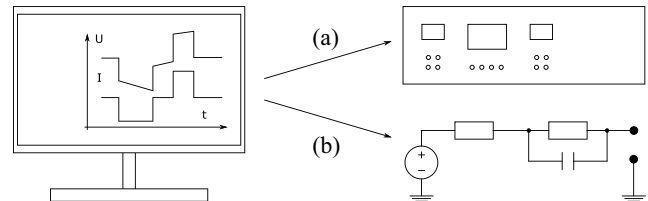


Fig. 2. To avoid influence on the learning effectiveness, the hands-on device (a) or the simulation model (b) was controlled by the same graphical user interface [27]–[29], [31].

had the chance to ask questions regarding the experimental procedure. Afterward, the students were grouped into small working teams and connected the prepared cell to the device (hands-on) or started the simulations (simulated). All student teams worked autonomously in a supervised environment following written instructions. To start an experiment, students defined a current and voltage sequence (including a temperature profile in some cases) for each measurement. All laboratory experiments consisted of a series of measurements to collect data (current, voltage, and temperature over time), which were evaluated before the next measurement or later at home, to produce the requested graphs (e.g., internal resistance over temperature) or conclusions. All the learning targets were addressed in the proposed experimental procedure and did not require essential explanations from the instructor.

### C. Laboratory Environment/Devices and Simulations

A safe and easily manageable battery test system was developed for the hands-on laboratory experiments (Fig. 1). It supported temperature-dependent experiments with different cell types including lithium-ion cells, and incorporated a redundant safety shut-off module that protected students from being injured [27].

All the measurement equipment was controlled by a specially created Java computer program “MSCS,” which was the same in both modes (Fig. 2) [28]. Thus, the user interface was identical in both modes (Fig. 3). The MSCS program allowed to design and execute all test sequences for battery analysis. Therefore, exercises in the three content areas ( $B$ ,  $C$ , and  $D$ ) did not require physical interaction with the measurement devices or batteries while the experiments were running. The MSCS program presented the measurements in a real-time graph and supported time-discrete data export.

To guarantee that the experimental results achieved in the simulation mode were similar to those of the hands-on mode, battery cells were analyzed in order to parameterize the underlying simulation model (Fig. 4). As a result, simulations

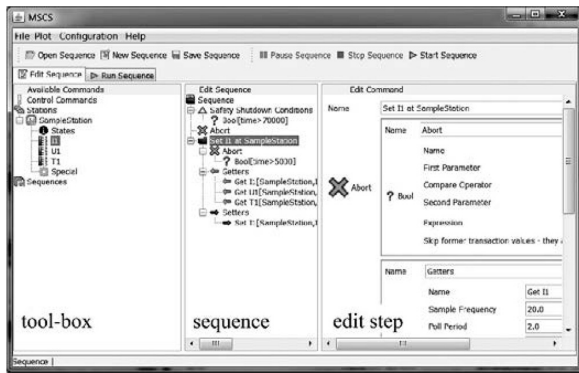


Fig. 3. Graphical user interface, which was used to control the experiments in both learning modes. On the left column (toolbox), the available devices are shown. By adding nodes in the center column (sequence) the user adds phases to the test sequence. Drag and drop operations from the toolbox allow intuitive usage. On the right column (edit) the user can configure the phase of the sequence, for example, a constant current injected for 5 s.

closely imitated the actual behavior of battery cells. Only the input and output data were visible to students. The model itself, as well as the cell parameters and internal computed values of the simulated cell have not been released to students (black-box model). Such an arrangement ensured that all participants involved in simulations had the same information as their peers working in the hands-on condition. The simulation of cell behavior always started after opening the control software regardless of whether experimental procedures were running or not. Thus, the simulated cell behavior also included aspects regarding the global design of the experiment (e.g., showing the cell cooling down for an appropriate time between two experiments).

#### D. Methodology of the Educational Experiment

All laboratories were conducted after the group formation. To analyze the effect of the learning mode on students' learning, data of written tests were collected. These tests did not influence students' grades.

1) *Assessing the Amount of Practical Experience of the Participants:* Personal interest can be seen as a precursor for learning success since it has a profound effect on cognitive functioning, including but not limited to focus and attention as well as knowledge gain [32]. A widely renowned concept that describes interest on a general level is Holland's RIASEC-typology, in which six personality types are distinguished (realistic, investigative, artistic, social, enterprising, and conventional) and are connected to a wide array of attitudes, values, and self-beliefs [33]. However, this concept is too broad to capture students' interests in a science-based topic [34]. Therefore, a questionnaire was created that comprised of items asking about prior experiences in practical tasks (as well as self-beliefs) similar to questions used by inventories based on the RIASEC-model but with higher specificity toward technical practical experiences. For example, "I have assembled a model kit." or "I have realized a function using a self-made circuit diagram." The questions were rated on a four step Likert-type scale [yes (1.5)/rather yes (0.5)/rather no (-0.5)/no (-1.5)]. The average value of the student's responses was considered the *amount of practical experience* of the student as shown in Table II. A value above

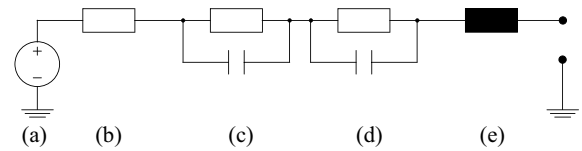


Fig. 4. Simulation model of the electrical characteristics of the battery cell. (a) Open circuit voltage. (b) Internal resistance. (c) and (d) Cathode and anode double-layer capacitance and charge transfer resistance. (e) Inductance. Such models are widely used in battery simulation/characterization to meet the frequency-dependent behavior of cells (e.g., [30]). In the actual case, the model was extended by state of charge and temperature-dependent behavior of (b).

zero indicated that the participant had prior practical experience with most of the items listed in the questionnaire, while a value below zero indicated little prior experience. It was used to rank students in accordance with their level of practical experience. This questionnaire was distributed only amongst the participants of three runs (R1, R2, and R5) during the introductory session. With Cronbach's  $\alpha = 0.80$ , the scale had a high reliability [35].

2) *Group Formation:* Since students with more practical experience may behave differently than their colleagues with less practical skills and group interactions must be considered [36], [37], the following method was used to create two groups of participants with similar practical experience in R1 and R2. Participants were sorted in descending order according to their respective amount of practical experience. The first and the fourth on the list of participants were assigned to group A, while the second and the third were assigned to group B. This procedure was repeated until all participants were assigned to either group A or B.

With their diverse backgrounds, participants of the international summer school (R3) were assigned to their groups manually, based on their respective fields and the year of study in order to create two homogenous groups. For the guest laboratory trial (R4) and the master's program (R5), group formation was arranged randomly.

After being divided into two groups, students of each group were allowed to select partners in order to conduct laboratory experiments in small working teams of three to five. To ensure the same cooperative learning conditions, team partners did not change for the whole duration of laboratory work.

3) *Conducting Laboratories in Content Areas A–D:* For the simulation experiments of the content area A, a special web-based application was used, while the aforementioned black-box simulation model was used for all other content areas.

Groups in the study runs that were conducted in German (R1, R2) performed the same experiment on two separate weekdays. In all other runs, both groups conducted the laboratory simultaneously and in the same room; as both laboratory experiments in R3, R4, and R5 were conducted on the same day, the groups switched to the other mode for the second content area.

4) *Assessing Knowledge Acquisition:* Written tests were used to assess the effect of the learning mode on students' results using a mixture of item formats (descriptive, single-choice, multiple-choice, drawings, and graphs).

TABLE III  
TESTS

Test	Questions N	Max. points per question	Points sum	Points avg. per question
A – R1, R2	10	2	17	1.70
B – R1	10	2	16	1.60
B – R2	9	2	15	1.66
C – R1, R2	12	2	15	1.25
D – R1, R2	9	2	11	1.22
B*, C* – R3-R5	12	5	25	2.08

The following is an example of a simple single-choice question: “The state of charge is stated in percent. Which physical dimension does it relate to? (Which quantity is stated in percent?).” Different physical dimensions (voltage, current, charge, impedance, and energy) were given.

Graph tasks involved describing test procedures or battery cell behavior (e.g., internal resistance dependent on temperature). A typical graph task is shown in Fig. 5.

Other tasks required students to explain relationships based on sketches, for example, arrangements of measurement equipment or the physics behind temperature gradients in a cell. Some tasks also included calculations. For example, the discharge time, depending on a given C-rate. Here, students were expected to carry out calculations before answering the question.

In addition, the test included questions on typical values covered in the respective laboratory experiments, like the allowed voltage range of a lithium manganese dioxide cell.

The participants were given 10 min to complete each test. Since the environment influences test results [38], tests took place in the same environment regardless of the experimental condition [41]. Participants of the study runs held in German (R1 and R2) took the tests one or two weeks after the respective laboratory exercises were conducted, prior to the next laboratory session. In order to equalize the influence of time on the ability to remember, equal periods of time were targeted between experimentation and the associated tests for both groups [25], [41]. Students that participated in the study runs conducted in English were handed a single test between one and two weeks after completion of the laboratory work. These tests covered all the materials studied during the laboratory sessions. Tests submitted by students who did not attend the respective laboratory experiment were excluded from the experimental data. In all runs, the test results did not have any influence on the participants’ grades. All tests (see Table III) were graded by the same person using a positive point system. Percentages of scored points relative to the maximum score were calculated per content area (partial credit was awarded). In order to determine which laboratory mode produced better student learning, the average test results in the two experimental conditions hands-on and simulated were compared.

### III. RESULTS

#### A. Test Results

Average test results and respective standard deviations are presented in Table IV. All study runs (R1–R5) showed a tendency toward better knowledge acquisition in the hands-on condition. The last row shows the results weighted per test

1.4 Complete this two diagrams to a typical CC-CV discharge of a lithium-ion cell. Label all axes. Name the units.

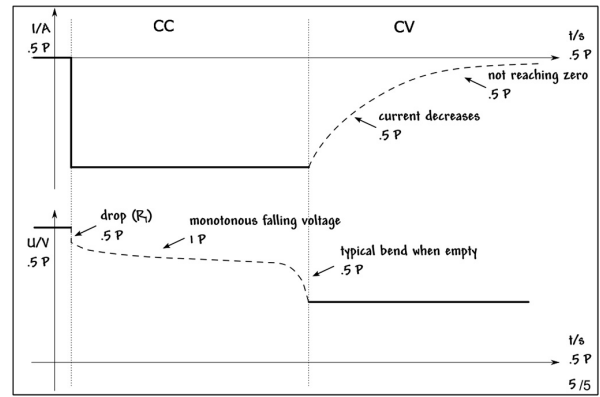


Fig. 5. Example task of the written tests. Students had examined constant current/constant voltage (CC–CV) charge and discharge in their experiments. The text “CC” and “CV” and the straight lines were given. The students were expected to identify the two graphs and label the axes. Additionally, they were asked to add the missing cell behavior.

(i.e., students from double-crossover-experiments, taking four tests instead of two, count twice in this row). Throughout all runs, participants’ test results indicate a reasonable knowledge retention with mean test scores ranging from 44% to 69%. Students met the expectations of teachers; the level of the tests was chosen according to the students’ knowledge after learning.

An independent-samples *t*-test was conducted to compare both experimental conditions. Although student test scores in each individual study run after hands-on exercises outperformed those after simulations, the differences in the individual study runs were not statistically significant.

Student performance after hands-on laboratories significantly exceeded student performance after simulation in the German runs [R1 and R2,  $t(261) = 2.25, p < 0.026$ , Cohen’s  $d = 0.28$ ], while in the international runs (R3–R5) only a slight effect toward hands-on mode was detected, which was not significant.

Across all study runs, the students’ test scores differed statistically significant between the modes and were, after hands-on experiments, higher than after simulated laboratories [R1–R5,  $t(371) = 2.47, p < 0.015$ , Cohen’s  $d = 0.25$ , small effect].

An independent-samples *t*-test was conducted to compare results grouped by the different item formats. The results are presented in Table V. While all formats showed advantages of the hands-on condition with slight to small effect strengths, only the scores of multiple-choice and single-choice tasks differed statistically significantly between both compared modes. These two formats were the most frequently asked.

Differences between the difficulties of item formats were found. While single-choice items were answered correctly in 75% of the cases, 41% of multiple-choice questions and only 31% of descriptive tasks were solved.

Table VI presents the results of independent-samples *t*-tests comparing the results of both conditions grouped by main learning objectives. For all learning objectives, scores were higher after the hands-on condition. Scores of “Battery Behavior” and “Battery System Design” did not

TABLE IV  
STUDENT'S TEST RESULTS GROUPED BY STUDY RUN: COMPARISON OF EXPERIMENTAL CONDITIONS

Study run	Hands-on			Simulated			df	t	p	Cohen's d (pos. = adv. of hands-on)
	Tests	Mean Score	SD	Tests	Mean Score	SD				
R1 Electric Mobility (B. Eng.) 2016	73	47%	17%	75	44%	18%	146	1.33	0.185	0.22
R2 Electric Mobility (B. Eng.) 2017	58	56%	17%	57	49%	23%	113	1.84	0.069	† 0.34
R3 International Summer School	28	60%	23%	28	56%	24%	54	0.57	0.572	0.15
R4 IEEE guest laboratory	9	55%	30%	9	47%	21%	16	0.68	0.505	0.33
R5 Renew. Energy Syst. (M. Sc.)	18	69%	18%	18	62%	24%	34	1.00	0.325	0.33
R1 & R2: Electric Mob. (B. Eng.)	131	51%	17%	132	46%	20%	261	2.25	0.026	* 0.28
R3, R4 & R5: International Runs	55	62%	23%	55	57%	24%	108	1.23	0.211	0.23
All test results	186	54%	20%	187	49%	22%	371	2.47	0.015	* 0.25

The last row shows the results weighted per test (i.e., students from double-crossover-experiments, taking four tests instead of two, count twice in this row).

† =  $p < 0.10$ , \* =  $p < 0.05$

TABLE V  
TASK RESULTS GROUPED BY ITEM FORMAT

Item Format	Hands-on			Simulated			df	t	p	Cohen's d (pos. = adv. of hands-on)
	N	Mean Score	SD	N	Mean Score	SD				
Draw/Graph	145	56%	36%	146	54%	41%	289	0.46	0.648	0.05
Draw/Sketch to explain	134	47%	44%	134	43%	43%	266	0.81	0.421	0.10
Multiple-choice	422	44%	46%	423	37%	44%	843	2.21	0.027	* 0.15
Single-choice	528	78%	42%	537	71%	45%	1063	2.51	0.012	* 0.15
Text/state or calculate a value	300	58%	47%	316	54%	46%	614	0.87	0.387	0.07
Text/state reason or equation	135	34%	41%	129	29%	38%	262	1.10	0.273	0.14

\* =  $p < 0.05$

TABLE VI  
TASK RESULTS GROUPED BY MAIN LEARNING OBJECTIVES

Main Learning Objective	Hands-on			Simulated			df	t	p	Cohen's d (pos. = adv. of hands-on)
	N	Mean Score	SD	N	Mean Score	SD				
Battery Behaviour	793	58%	46%	809	55%	47%	1600	1.24	0.215	0.06
Battery Parameters	231	66%	45%	220	56%	46%	449	2.29	0.023	* 0.02
Battery System Design	160	56%	46%	170	54%	47%	328	0.47	0.638	0.05
Experimental Setup	480	54%	46%	486	46%	46%	964	2.63	0.009	** 0.07

\*\* =  $p < 0.01$ , \* =  $p < 0.05$

differ significantly between both modes, whereas the scores of “Battery Parameters” and “Experimental Setup” showed statistically significant differences with small effects.

Of the 44 different questions used, 28 showed effects (Cohen's  $d > 0.05$ ) toward hands-on mode, while 11 items pointed in the direction of simulations (Cohen's  $d < -0.05$ ). Only one of these 11 items showed statistical significance ( $p < 0.05$ ), while four items presented a statistically significant trend toward better learning with hands-on experiments. An analysis was performed to check if the frequency of the chosen item format influenced the results regarding the individual learning target and vice versa. No correlation was found. Both for the item formats and the learning objectives, broadly distributed data contributed to the overall trends.

### B. Vocational Education and Training

For the 2017 bachelor's program study run (R2), the survey on practical experience (see Section II-D-1) was enhanced to collect additional details about individual students. The students were asked if they had completed a German vocational education and the training (VET) program (refer to the Appendix for background information) before their studies. A Spearman's rank correlation coefficient was computed to

assess the relationship between the self-reported amount of practical experience and the completion of a VET before studies. A positive correlation between the two variables was found [R2;  $N = 27$ ; Spearman's  $\rho(25) = 0.50$ ,  $p < 0.008$ ]. Students who completed VET reported a significantly higher amount of practical experience than their colleagues [39].

To evaluate the relationship between the completion of VET before studies and the test scores of both learning modes separately, independent-sample t-tests were computed.

Students with VET before studies learned better with hands-on experiments compared to simulations [R2;  $t(58) = 2.24$ ,  $p < 0.030$ , Cohen's  $d = 0.56$ ], while for non-VET participants the difference between modes was not statistically significant.

After *hands-on* laboratories, students with and without vocational training achieved practically identical test results. Whereas after *simulated* laboratories, test scores of students who had not completed a VET program statistically significantly exceeded the scores of participants with a VET degree [R2;  $t(46) = 2.11$ ,  $p < 0.040$ , Cohen's  $d = 0.62$ ], indicating a medium to large effect.

Nevertheless, a higher amount of practical experience (R1, R2, and R5) was not significantly correlated to students' test results in the single experimental conditions.

#### IV. DISCUSSION

While the positive effect of laboratories on student learning has been widely accredited, optimal modalities of laboratory experiments have not been established with certainty. This study set out to add to the existing body of knowledge by comparing the impact of two different modes of laboratory work on learning while minimizing the influence of as many interfering factors as possible. For each of the five independent study runs, the mean student test scores after hands-on laboratories were higher than after simulated laboratories. However, the difference was not statistically significant. The results for all 129 participants revealed a statistically significant difference between test results after hands-on and simulated laboratories that favor the former. The most unexpected was a statistically significant lower performance after simulated laboratories of students who had completed a vocational training prior to their studies when compared to the performance of the rest of the class.

There are several study limitations that need to be addressed. Over 70% of the research data were based on the test results of participants from one German university of applied sciences (Technische Hochschule Ingolstadt) enrolled in the same B.Eng. program (electric mobility). In addition, a significant number of German participants completed a VET program before enrolling at the university. The proportion of students with vocational training at enrollment in this B.Eng. program (46%) slightly exceeds the average of VET graduates enrolled in bachelor programs at the THI Faculty of Electrical Engineering and Computer Science (38%) [40]. Moreover, 59% of the students participating in the German B.Eng. 2017 run (R2) had completed vocational training. Therefore, it can be argued that the statistically significant difference in test scores shown in Table IV both for all participants (373 tests) and for German participants (263 tests) can be attributed to the high number of German VET graduates that took part in this study. If they had not participated in the study, students' scores as a result of hands-on and simulation laboratories might have been identical in both groups. Furthermore, the differences between the two conditions during international study runs were less significant. Nevertheless, better knowledge acquisition with hands-on laboratories is supported by the similarity of the effect size for the international (R3–R5) study runs and the German-only (R1 and R2) runs.

In all runs, the majority of participants were male (>75%). Results are therefore not generalizable to student populations with a higher ratio of female participants.

Another limitation that needs to be considered is the participants' motivation. Students from different study runs participated in different learning contexts (semester versus summer school). As the international programs were obviously visited by motivated students who took it upon themselves to travel to Germany for their studies, their motivation to get the most out of the learning experience was possibly higher compared to students from the other groups. While the participants' motivation was not controlled for, the mean scores and standard deviations of their test results do not indicate substantial differences between international students and the German groups. In addition to this, no extrinsic incentives

were offered to the participants, so it is reasonable to assume that their motivation was based on their own interest in the subject.

Much effort was spent on designing simulations that realistically imitate battery behavior. No perceived differences in battery behavior were found in the students' protocols. Nevertheless, it was not possible to exclude hidden deviations of the simulation model completely. These might have influenced students' learning.

Test results across all runs showed a statistically significant difference in test scores favoring the hands-on laboratory mode. Assuming that students gained knowledge and skills during the laboratories, subsequent performed experiments and tests should have been easier to manage. Since the effect sizes of each run as well as the overall effect size point toward better results in knowledge acquisition/retention when conducting hands-on laboratories compared to simulated ones, it is plausible to argue that the differences in performance between groups would have been more significant, had the participants been allocated to either the hands-on or simulated laboratories across all experiments.

When looking at the different conditions, it must be noted that students monitored currents and voltages displayed on a computer screen in both modes. During hands-on laboratory exercises, students also had the option to check currents and voltages that were displayed on the measurement equipment. Similar to the students conducting simulations, they had to trust that the displayed currents and voltages were correct. Moreover, the experiments for the content areas B, C, and D did not involve any physical interaction with the equipment during hands-on experiments, as measurement equipment was controlled by software.

In order to comprehend the effectiveness of different laboratory modes more fully, psychological effects should be considered. Perhaps, the absence of a physical device and/or a real battery have been perceived differently by students with and without a VET degree. The VET graduates could have felt that simulated experiments were less relevant, and they might have lost interest and therefore motivation to comprehend or remember what they had experienced during the laboratory exercises.

#### V. CONCLUSION

In several study runs in 2016/2017 that involved 129 engineering students, test results related to knowledge acquisition as a result of conducting laboratory exercises in different modes were collected. This study applied a counterbalanced within-subject research methodology. It focused on the comparison of the laboratory modes hands-on and simulation. Accompanying lectures, experimental instructions, teachers, learning objectives, tests, and many other variables were controlled for both groups. Students learned more effectively while engaged in hands-on laboratories compared to simulated laboratories.

The results of the German 2017 study run (R2) indicate a significant impact of the laboratory mode on the students' performance depending on whether a participant had



completed a VET program or not. In the hands-on condition, German participants who had completed such a program prior to university enrollment performed similarly to their peers who enrolled in their university studies directly after high school. In contrast, simulated experiments had less positive effects on their learning. It needs to be noted that as these outcomes are based on the test results of only 30 students. More data collection is necessary to come to a definitive conclusion on the reasons for such differences. This finding, nonetheless, suggests a need to investigate the utilization of laboratories depending on the students' educational and industry background. It is possible that engineering educators need to consider offering students laboratory experiments in accordance with their prior learning and practical experiences.

Therefore, results suggest opting for hands-on laboratories when deciding between hands-on experiments and identically performed simulated experiments for two reasons. First, the hands-on condition resulted in better test scores. Second, it does not seem to be disadvantageous to students from different educational backgrounds. However, the overall effect sizes were small. Educators might need to promote the authenticity of the potentially applied simulation by explaining that it mimics the behavior of real equipment so well that it is practically impossible to discriminate between the two modes.

The study does not determine the best learning mode for battery lessons specifically, rather the goal was to evaluate the general influence of the learning modes on laboratory learning. Therefore, it is essential to mention that nearly identical experimental procedures were used in both modes. It is expected that the results would differ if the conditions were optimized separately according to their educational potential, for example, with simulations, using time lapse to teach battery aging or with hands-on experiments, training of optimal wiring for high-frequency impedance spectroscopy.

It is recommended that further studies utilizing the counterbalanced research methodology should be carried out in other engineering fields with different learning objectives and other types of higher education institutions to thoroughly validate the methodology and the results reported in this article. Additionally, a conventional randomized group comparison between hands-on laboratories and simulated laboratories is needed to gain insight into the differences in test results and effect sizes, if students only participate in one of the two laboratory conditions.

#### APPENDIX

##### BACKGROUND INFORMATION GERMANY'S DUAL SYSTEM OF VOCATIONAL EDUCATION AND TRAINING

More than 500 000 new contracts in the VET system are signed between trainees and companies in Germany each year [42]. More than 60% of young people in Germany take part in this system [43]. Successful completion of a VET, plus one year of additional schooling, entitles graduates to enroll with a university of applied sciences similar to students who completed Germany's standard secondary education (12 or 13 years, the so-called "Abitur") [44].

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