Laboratory Learning: Hands-on versus Simulated Experiments

Fabian Steger[a,b], Alexander Nitsche[b], Cayler Miley[c],
Hans-Georg Schweiger[b], and Iouri Belski[a].
School of Engineering, RMIT, Melbourne, Australia[a],
Faculty of Electrical Engineering and Computer Science, THI, Ingolstadt, Germany[b]
Faculty of Computer Science and Engineering, UNR, Reno, USA[c]
Corresponding Author Email: fabian.steger@thi.de

SESSION C1: Integration of theory and practice in the learning and teaching process

CONTEXT Many universities and vocational training institutions conduct laboratories as simulated experiments. This is due to the costs and supervision needs to conduct hands-on labs safely. Numerous studies have presented mixed opinions on whether hands-on laboratory work is more conducive to learning than a simulated laboratory. Most of the studies put students from experimental and control groups in significantly different conditions. Therefore, it is hard to reach any definite conclusion regarding the influence of the learning mode onto the learning achievements.

PURPOSE This study compares learning outcomes of student laboratory work in an energy storages course conducted in two different modes: first as a practical hands-on exercise and second using computer-based simulations.

APPROACH In order to provide reliable insights, this study implements optimized research methodology to avoid any other effect (e.g. learning synchronicity/distance learning/instructions) on the learning outcome rather than the effect of the learning mode itself. The student laboratory experiments were created in a manner that they could be conducted in both modes in the same way and using a single set of instructions. To ensure a comparable group environment for the individual student, the students were arranged into two similar groups based on the student's practical experience. In this crossover study, the groups were taught the same topics by means of interchanging learning modes.

RESULTS To evaluate the influence of each mode on student learning, short written tests regarding the previous experiment were conducted at the beginning of the subsequent laboratory session. 102 students have taken part in the study in two years. Overall learning results of hands-on experiments were slightly better than those of simulated laboratories (Cohen's d=0.25), the difference in performance was statistically significant ($p<0.02$). Through solicited feedback on each laboratory session, in hands-on mode more students expressed they have acquired new insights/comprehensions (76% vs. 66%, Cohen's d=0.23, small effect, $p<0.07$).

CONCLUSIONS Following the strategy not to optimize the lessons individually to the learning mode, other influences on the learning outcome, which were usually mixed, were excluded. The students' subjective opinions show advantages of the hands-on mode. Based on the objective data, a weak, but significant outcome to better knowledge acquisition with hands-on laboratory experiments was achieved. This observation is against the trend of the literature in the last years towards better or equal learning with nontraditional labs. Some of the excluded factors might have a stronger influence on student learning than estimated previously. To get a clear view, the authors recommend isolated research.

KEYWORDS Hands-on vs. simulated experiment, battery experiment, learning-mode comparison

Introduction

Many universities and vocational training institutions conduct laboratories as simulated experiments instead of using the traditional hands-on way (Ma 2006, Brinson 2015, Heradio 2016). One reason is the cost of required lab equipment to conduct hands-on experiments. In case of potentially dangerous learning objects – like lithium-ion cells (Dahn 2011) – additional supervision is necessary to conduct traditional labs safely.

This study compares learning outcomes of student laboratory work conducted in two different modes: first as a practical hands-on exercise and second using computer-based simulations. Previous studies have presented conflicting outcomes (Ma 2006, Brinson 2015, Heradio 2016, e.g. Mathiowetz 2016, Sarabando 2016). After comparing the results of such research, Ma and Nickerson (2006) concluded that many studies did not allow to reach universally applicable conclusions.

Most of the studies put students from experimental and control groups in significantly different conditions. This is a result of separately developing and optimizing the teaching experiment in each mode, as the teachers/researchers do not see the modes as directly competing solutions for exactly the same objective, they prefer to accommodate different circumstances with both modes. For example, students conduct hands-on experiments in groups whilst on campus, but as off-shore students they are engaged in simulated exercises over the web and individually. Therefore, it is hard to reach a definite conclusion regarding the influence of the learning mode onto the learning achievements based on this kind of studies. As the change of modes is linked with other influences on the learning outcome (like changing learning objectives in the two modes, amount/type of supervision, cooperative learning effects, distance learning vs. learning in the university, and/or differing instructional papers) such studies always compare the combination of aspects. If these interfering aspects have stronger influences, the studies are unable to specifically identify the difference in learning effectiveness of one aspect (Lindsay 2005). This may explain the inconsistent outcome of present research (Ma 2006, Brinson 2015). Most of these other influences are difficult to describe clearly in written form, or just not mentioned in the publications. In order to provide more reliable insights, the present study follows an optimized research methodology to avoid many other influences on the learning outcome while comparing the modes. The student experiments were strictly developed in such a manner that the learning objectives and experimental procedure were matching in both modes.

Approach

In a crossover study, both groups were taught the same objectives, clustered into four content areas. All of the content areas were related to lithium-ion cells or battery systems. The first group learned the first and third area with traditional hands-on experiments while the second group was taught the same areas by computer-based simulations. The second and fourth areas were taught using the opposite learning mode in both groups.

In the beginning of the next laboratory session 10-minute long tests were conducted to evaluate the influence of the mode on student’s knowledge on the content areas of the previous experiment. To compare which mode has been more successful, the mean results for each group were evaluated. Moreover, the students were asked to reflect on their learning during each session in an online survey.

The experiment was conducted three times. Forty students of the study program "Electrical Engineering and Electric Mobility" at Technische Hochschule Ingolstadt (THI) were enrolled in the mandatory laboratory subject in summer-semester 2016. Thirty THI students were enrolled in summer-semester 2017. All students were asked to join the full anonymous study. Additionally an international summer school was included in the study to collect a broader database.

Learning objectives of the laboratory

It was decided to teach the most relevant transferable skills and knowledge that may be beneficial for the students' future careers. Thus, students should get familiar with the characteristic behavior and the most important parameters of battery cells. They should also gain knowledge on how to determine the parameters of battery cells self-sufficiently by means of appropriate experimental setups.

The recognized learning objectives where clustered into four main content areas: (A) contact and isolation resistance, (B) open-circuit voltage, (C) internal resistance and power, and (D) energy of cells. Grouped in these areas, seven laboratory experiments were conducted in both modes in the same manner:

- Low Resistance Measurements (A1): Students discover that a multimeter is an inaccurate tool for low ohmic measurements (milliohm range), and why such measurement is a misuse of this tool. They learn how to use alternative procedures for low ohmic measurements, including the four-wire measurement in AC and DC.
- Contact Resistance (A2): Students conduct experiments with a variety of typical electrical connections in battery systems to determine the contact resistance values.
- Isolation Resistance (A3): Students learn to estimate the influence of moisture on the isolation resistance.
- Voltage Curve (B): Students investigate the voltage of a cell depending on the state of charge. They use two different types of lithium-ion cells.
- Internal Resistance (C1): Students learn to use AC- and DC-methods to measure internal resistances, being aware of the temperature dependency of battery cells. Students learn to approximate temperature changes caused by power loss inside a cell.
- Power (C2): Students investigate the maximum discharge rate of battery cells. Students discover the dependency of maximum discharge power from state of charge, pulse duration, and temperature.
- Energy and Capacity (D): Students determine the capacity of a lithium-ion cell and learn about the factors influencing it. They learn to calculate the energy efficiency of charge and discharge cycles.

Each experiment was developed in parallel for both modes. Only a single set of instructions was created and then used in both laboratory modes, as instructions affect the learning outcome of an experiment, e.g. Chamberlain 2014 found, that the guidance level can influence student exploration.

Creating two comparable groups for the crossover study

In a crossover study, differences of the compared groups' average performances may be equalized by statistics. Nevertheless, with the goal of isolating the influence of the learning mode in the experiment, the authors had to consider the in-group interaction in laboratories. The same student may have different experiences in different groups, with consequent effects on his or her learning (van der Laan Smith 2007, Webb 1989). It was assumed that students with more practical experience might perform differently than their peers with a lesser practical background. Therefore the authors tried to create each of the two laboratory groups from students with a similar mix of practical skills. For the two study semesters of 2016 and 2017, an introductory questionnaire that asked students of their practical experience was developed. Its results were used for the group allocations. While completing the questionnaire, each student created a code-word that was used in the study to allocate the responses and test results to the appropriate individual, while keeping all participants anonymous. These code words were also used to assign students into laboratory groups. (Steger 2016)

Thirty-two students from the international summer school were allocated to groups to ensure similar distribution of the field of studies, number of study semester, and the nationality of the students in each group.

Conducting laboratories in content areas A to D

For each of the four main content areas a session with practical hands-on experiments and a session with computer-based simulations were established. Planned as a crossover study, each group followed the same sequence of contents, while alternating the learning mode between sessions. The first group handled the first content area with a computer-based simulation while the second group conducted it as a hands-on experiment. For the upcoming session both groups switched between learning modes. For the first content area, a specially created web tool was used for simulations. For the other areas a black box simulation of the battery cell and the hands-on equipment (Steger 2017a) was used. The battery simulation imitates all effects observed in the student experiments and was parameterized to match the battery cells which are used in the hands-on mode. To avoid any influence from user's interface, in both modes the simulation model was controlled by the same graphical user interface, a program to create the sequences for testing batteries. In both groups students selected companions to work in small teams of three to five students on the experiments. All groups and teams remained constant to avoid changing cooperative learning while the conduction of the semester lasting educational experiment. The laboratories were developed in a way to be conducted autonomously by the students in a supervised environment. All the learning targets were addressed through the experiment procedure/instructions, without essential explanations from the instructor. To pass the subject all learning teams had to prepare a written laboratory report for each content area.

During international summer school two trimmed content areas were taught on the same day; the same crossover principle was used as during ordinary semesters in 2016 and 2017.

Online survey after conducting the experiments

All student participants excluding that of the international summer school were asked to express opinions on their laboratory learning in a short online survey. It was conducted fully anonymously using the university's digital learning environment. Responses to the following survey questions were compared in order to evaluate the laboratory learning in both learning modes:

(a) "By conducting the experiment I gained new insights/comprehensions today." (German: "Ich habe heute durch den Versuch neue Erkenntnisse gewonnen.") This was a yes/no answer and coded 1 or 0.

(b) "At which point in the experiment did you have the biggest problem proceeding with the experiment?" (German: "An welcher Stelle im Versuch hatten Sie am meisten Probleme voranzukommen?") This was a free text question, which was not compulsory. For data evaluation, the information was coded to 1 if any problem was mentioned or to 0 if students wrote nothing or were expressing they had no problems.

(c) "The procedure of the experiment is quite difficult (1) / feasible (0.5) / easy (0)" (German: "Die Versuchsdurchführung ist recht schwer / machbar / leicht") The answers were coded in a three step Likert scale.

(d) "The content of the experiment is also relevant for me outside the university; I can imagine that it will be beneficial for my future professional life." (German: "Der Inhalt des Versuchs hat auch außerhalb der TH Relevanz für mich; ich kann mir vorstellen, im Berufsleben Gewinn aus dieser Versuchsdurchführung zu ziehen.") The answers were coded in a five step Likert scale: fully agree (1) / somewhat agree (0.75) / maybe (0.50) / somewhat disagree (0.25) / disagree (0)

Testing the learning outcome

Three written knowledge tests - each lasting 10 minutes - were used to determine the influence of the learning mode on student learning outcomes. Knowledge gained by students in a laboratory was tested just prior to the next laboratory session. A mix of descriptive and multiple-choice questions, free response, and drawings on the learning objectives of the previous experiment were used. The results were evaluated using a positive point system. The achievable number and the distribution of the points were set fixed beforehand.

As the tests were conducted anonymously, the students were distinguished by their self-created code words that were created by individual students during the Questionnaire on practical experience.

To exclude time influence on memorizing knowledge the authors aimed for equal time lapses between two sessions and thereby between experiments and its corresponding tests for both compared groups. Unfortunately this goal was not achieved regarding content area A in 2016 (Steger 2016). By conducting the sessions for both groups on the same day of the week it was easier to keep the time gap between the experiments and tests equal for both learning modes in 2017.

Independent of the learning mode, the same environment was established for both groups during tests. All students were able to sit at a desk in the same computer laboratory while working on the knowledge tests.

To find out which mode provides better learning outcome, average results for the test for each group were compared between hands-on and simulated modes.

Assessment of the influence of the study mode on learning outcomes of students that participated in the international summer school was similar to that of the students of peers that conducted laboratories during study semester. Due to logistical constrains, though, tests on the laboratory knowledge were administered to students as an examination one week after the experiments.

Results

Learning outcomes based on written tests

In year 2016 with 40 students for three content areas (A to C) a weak effect towards benefits of the hands-on mode was discovered. Hands-on laboratory sessions led to a better knowledge acquisition compared to simulated experiments. Content area D showed no difference between the modes. Overall learning results of hands-on experiments were slightly better than those of simulated laboratories (weak effect, Cohen's d=0.22), but the difference in performance was not statistically significant. (Steger 2016)

The second experimental run was conducted with 30 students in summer semester 2017. The range of individual scores was from 20% to 79% for hands-on, and from 15% to 77% for the simulated mode. For content areas A (d=0.50) and D (d=0.80, $p<0.02$) an effect towards benefits of the hands-on mode was measured. Content area C resulted in a weak effect (d=0.14) in the same direction, and content area B showed no difference between the modes. This run was demonstrating hands-on laboratory sessions led to a significant better knowledge acquisition compared to simulated experiments (d=0.34, $p<0.05$).

Additionally the learning outcome of 32 participants of the international summer school 2017 in Ingolstadt was evaluated. A short version of content areas B and C1 was taught. Independent samples T-test showed that content area B had no effect (d=-0.09), and content area C1 demonstrated a small to medium effect towards better learning in hands-on mode (d=0.44).

Overall learning results of hands-on experiments were slightly better than those of simulated laboratories (small effect, Cohen's d=0.25), the difference in performance was statistically significant ($p<0.02$). The correlation between an individual student's overall performance in the knowledge tests and learning better with simulations is very weak and insignificant (Pearson correlation 0.12, p=0.37, N=53).

Table 1: Learning Results Comparison

Research run	Number of Students	Std. Deviation of Percentage Points	Sample size N	Mean Value of Points	Sample size N	Mean Value of Points	effect size / Cohens d (pos = adv. of hands-on)	Student's t distribution / p-value one-tailed
		Both modes	Hands-on		Simulated			
THI 2016	40	17%	73	47%	75	44%	0.22	0.09
THI 2017	30	20%	58	56%	57	50%	0.34	0.03
THI SS 2017	32	24%	28	60%	28	56%	0.15	0.28
ALL	102	20%	159	53%	160	48%	0.25	0.014

In the 2017 research the pre-questionnaire was extended to ask for more detailed information. There was no correlation found between average mark in the study program and individual more effective learning mode (Spearman rho=0.03, N=24). Students who had not studied directly after school, but made a German VET (Vocational Education and Training, BMBF 2016), which is a dual (company & school) apprenticeship training and studied later (1st) have more hands-on experience (Pearson r=0.50, p=0.008, N=27) and (2nd) learn better with hands-on experiments compared to simulations (Pearson r=0.53, p=0.007, N=25) as they (3rd) have comparatively bad results with simulated experiments (Pearson r=0.47, p=0.017, N=25).

Online survey for student feedback

The student feedback results are based on all results of the first and second summer semester iteration. Student feedback was not collected during the summer school due to time constraints. Because fewer students responded to the questionnaire in 2016 (37%), an incentive was offered for completing the questionnaire in 2017 (Steger 2017b). The minimum passing score of 50% was reduced to 45% for participation in the online survey. As a result the return rate increased to 70% in 2017.

(a) In hands-on mode more students expressed they have acquired new insights/comprehensions (76% vs. 66%, Cohen's d=0.23, small effect, p<0.07).

(b) Slightly more students mentioned problems while conducting the hands-on equivalents (45% vs. 39%, Cohen's d=0.12, not significant, very weak effect).

(c) The engagement in the simulated experiments was stated to be a very small amount (5% of scale) more difficult. Cohen's d=-0.16 demonstrates a very weak effect, which was not significant.

(d) In the feedback form on the experiments, students who conducted the experiments in the hands-on mode rated the execution of the experiments a little more beneficial for their future professional life (58% hands-on vs. 54% simulation, Cohen's d = 0.20, small effect).

A significant correlation between (a) and (d) was found. It shows that students who claimed that they gained new insights also tend to believe that the execution of the experiment will help them in their future professional life (Pearson's r=0.36, p<0.001, Spearman's rho=0.35). Looking at both modes separately, this correlation in the simulation mode was little stronger (Pearson's r=0.39, p<0.001; Spearman's rho=0.40; N=86) compared to the hands-on mode (Pearson's r=0.30, p=0.115; Spearman's rho=0.27; N=92).

Interesting is a significant weak correlation that exists only in hands-on mode: Students who (c) stated a hands-on experiment difficult, tend to not (d) consider it beneficial for their future professional life (Pearson's r=-0.23, p=0.017; Spearman's rho=-0.22; N=86). Regarding simulated experiments Pearson's r and Spearman's rho is 0.04.

The actual methodology does not allow establishing correlations between individual learning outcome and student's feedback, as the standard online feedback form did not ask for the self-created code word that was used in the tests. The authors plan to request this missing information by updating a questionnaire and use the information for the next iteration.

Conclusions

Learning outcomes based on written tests

Following the strategy not to optimize the lessons individually to the learning mode, other influences on the learning outcome, which were usually mixed, were excluded. Based on the existing data, a weak, but significant outcome of better knowledge acquisition with hands-on laboratory experiments was achieved. This is against the trend of the recent literature that reported on better or equal learning with nontraditional (virtual/simulated) labs (Heradio 2016, Brinson 2015). Some of the excluded factors might have a stronger influence on student learning than estimated previously. To get a clear view, the authors recommend isolated research. The study on the mode will be continued through 2018 at THI and at more universities and training institutions with different types of students (e.g. international students, students enrolled in summer schools).

The average performance in the knowledge tests of a single student is independent from his better performing learning mode. It is important to note that this is the result of the created group environment, and may differ if one creates groups of high and low performers.

The difference between students that completed German Vocational Education and Training before studies and those who enrolled at university directly after school was interesting. Obviously, the VET-participants have more hands-on experience. This fact was confirmed by the study. The group creation questionnaire distributed the VET-participants equally to both groups based on the hands-on experience without using the VET-info. In 2017, 59% of the participating students in the study were VET-participants. Looking at the correlational data, this group learns better with hands-on experiments compared to simulations, as they have significant disadvantages while taught by simulations. Checking the 2017 results of the knowledge test separately, confirmed this point of view: VET-participants had a significant better learning outcome with hands-on experiments (Pearson r=0.56, p<0.015, N=60 tests), while non-VET-participants had no significant difference (N=37 tests).

Online survey for student feedback

The students' opinions show advantages of the hands-on mode. The effect between both modes in the student's subjective opinion about gained knowledge (a) is very similar to the objective results tests, even when student’s expressions are less significant. Regarding mentioned problems (b) and stated difficulty (c) the experiments are considered equivalent. The slight, insignificant differences may be a result of statistical effects. To clarify this, more data collection is necessary. Asking the students to describe the laboratory difficulty in a free text answer may help to gain a deeper insight. Independent from the learning mode, more than forty percent of the students stated the opinion that they do not benefit in their future professional life from the experiments (d). There are slight advantages in the hands-on mode and it is planned to ask in future experiments for missing content students estimate as more important for their future profession.

The correlation between (a) and (d) suggests that students who believed that the execution of the experiment will help them in their future professional life also expressed that they gained new comprehension. The slightly stronger correlation between (a) and (d) in the simulations mode suggests that teachers should pay attention to explain the relevance of the experiment in simulated labs more carefully. Comparing the amount of positive answers in (a) and (d), one can conclude that the students do not consider all of the gained insights relevant for their profession. Identifying these insights may be beneficial for the improvement of the experiments. Future surveys will ask for the greater or lesser beneficial insights gained and whether these are considered useful outside the university.

References

BMBF, German Federal Ministry of Education and Research (2016). *Report on Vocational Education and Training 2016.*

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories. A review of the empirical research. *Computers & Education 87*, pp. 218–237.

Chamberlain, J. M., Lancaster, K., Parson, R., Perkins K.K. (2014). How guidance affects student engagement with an interactive simulation. *Chemistry Edu. Res. & Practice 15*(4), pp. 628-638.

Dahn, J. & Ehrlich, G. M. (2011). *Lithium-Ion Batteries, Linden's Handbook of Batteries 4th Edition*, McGraw-Hill, pp. 26.1-26.79.

Heradio, R., de la Torre, L., Galan, D., Cabrerizo, F. J., Herrara-Viedma, E., Dormido, S. (2016). Virtual and remote labs in education. A bibliometric analysis. *Computers & Education 98*, pp. 14–38.

Lindsay, E. D (2005). *The Impact of Remote and Virtual Access to Hardware upon the Learning Outcomes of Undergraduate Engineering Laboratory Classes.* The University of Melbourne

Ma, J., Nickerson J. V. (2006). Hands-On, Simulated, and Remote Laboratories: A Comparative Literature Review. *ACM Computing Surveys 38*(3), Article 7

Mathiowetz, V., Yu, C.-H., Quake-Rapp, C. (2016): Comparison of a gross anatomy laboratory to online anatomy software for teaching anatomy. *Anatomical sciences education 9*(1), pp. 52–59.

Sarabando, C., Cravino, J. P., Soares A. (2016): Improving Student Understanding of the Concepts of Weight and Mass with a Computer Simulation. *Journal of Baltic Science Education 15*(1).

Steger, F., Nitsche, A., Schweiger, H.-G., Belski, I. (2016). *Teaching Battery Basics in Laboratories: Comparing Learning Outcomes of Hands-on Experiments and Computer-based Simulations,* Paper presented at the 27th Australasian Association for Engineering Education (AAEE) Annual Conference, Coffs Harbour.

Steger, F., Nitsche, A., Brade, K., Belski, I., Schweiger, H.-G. (2017a). *Teaching Energy Storages by means of a Student Battery Cell Test System,* Paper presented at the 45th European Society for Engineering Education (SEFI) Annual Conference, Angra do Heroísmo.

Steger, F., Nitsche, A., Schweiger, H.-G., Belski, I. (2017b). *Hands-on Experiments vs. Computer-based Simulations in Energy Storage Laboratories,* Paper presented at the 45th European Society for Engineering Education (SEFI) Annual Conference, Angra do Heroísmo.

Webb, N. M. (1989). Peer interaction and learning in small groups. *International Journal of Educational Research (13)*1, pp. 21-39.

van der Laan Smith, J., Spindle, R. M. (2007): The Impact of Group Formation in a Cooperative Learning Environment. In *Journal of Accounting Educatio*n 25(4), pp. 153–167.

Acknowledgements

This research was approved by the Faculty of Electrical Engineering and Computer Science of TH Ingolstadt and the College Human Ethics Advisory Network of RMIT, Melbourne.
The project "Academic Education Initiative for E-Mobility Bavaria - Saxony" and the Faculty of Electrical Engineering and Computer Science at THI provided funding which was used for the development and the production of the laboratory devices.
This research was not possible without students, generously ready to take part in the study to improve the learning outcome of future groups.