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Engineering Learning through Aerospace Engineering Laboratory

Sam Power
Student
Sheffield Hallam University
UK

Anne Nortcliffe
Principal Lecturer
Sheffield Hallam University
UK

Karen Vernon-Parry
Principal Lecturer
Sheffield Hallam University
UK

Torsten Schenkel
Sheffield Hallam University
UK

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Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
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Engineering Learning through Aerospace Engineering Laboratory

Sam Power
Anne Nortcliffe
Karen Vernon-Parry
Torsten Schenkel

Abstract

This paper presents the results of an investigation into identifying what is good engineering laboratory practice to maximise student learning. The UK engineering accreditation bodies require all engineering degrees to have a significant amount of laboratory based learning, yet the literature on how learners construct knowledge from engineering laboratories typically still cite Dewey (1910) [1]. The role of the laboratory, whether simulation or physical experimentation, is to develop: students' learning, students' ability to put theory into practice, and reflective habits, so that students become able to draw sensible conclusions from experimental data. Quantitative and qualitative methods were used to evaluate first year undergraduate aerospace students' ability to apply theoretical knowledge (gained from lecture and seminar) to tasks in an associated laboratory. The results indicate that undertaking a number of laboratories is important to assist in building student learning of a subject, and that a requirement to articulate their reflections and ability to assimilate knowledge from laboratory is critical to maximise the depth of learning from the laboratory. The results of this work are informing the future designs of the engineering laboratory space, and laboratory learning, teaching, assessment and laboratory lesson plans at Sheffield Hallam University.

Keywords: Engineering Laboratory Pedagogy, Engineering Practical Learning, Experimental Learning, Practical Learning.

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Introduction

Bloom's Taxonomy of Learning model [2] identifies the need for students to develop their knowledge through multiple cognitive models such as remembering, understanding, applying, analysing, evaluating and finally creating knowledge. This process develops metacognition, a (cognitive) process essential for being a successful engineer [3-9]. Engineering undergraduates require a deep understanding of the fundamentals of engineering and must develop an ability to apply this in practice to be a successful engineer in the work environment [10].

Laboratories are beneficial to a student's understanding as they actively involve the student in their own learning, promoting ownership of their learning [11] and developing higher levels of cognitive analysis skills [12-15]. Engineering practical lessons enable students to build upon and increase their level of understanding of the technical theoretical knowledge taught in lectures [16], and to apply this knowledge in practice, *"learning through doing"* [17]. The process of making mistakes and learning from them in a laboratory is an essential part of the development of problem solving skills, a key skills set to be an engineer, as engineering involves *"the process of analysing, modelling, experimenting and realising, in which many choices need to be made"* [18].

There is extensive literature on the pedagogy of science laboratories, however the definitive literature for engineering typically cites Dewey (1910) [1] on how learners construct knowledge from laboratories. There is a belief that engineering undergraduates are not ready for *'real-world engineering'*, as undergraduates often lack the ability to draw a connection between theory and practice [19-21]. However the UK engineering accreditation bodies require all engineering degrees to have a significant amount of laboratory based learning [22].

It is clear from research by the Engineering Education Network that there is a need for further development of engineering education methods to deepen students' knowledge and enhance their ability to draw on key engineering skills [23-24]. Instructional laboratories should be designed to develop students' engineering knowledge, understanding and application abilities; also identified was the importance of the chronological relationship between laboratory and lecture for student knowledge synthesis [10].

Practical engineering learning is typically developed in a laboratory environment [25]. Group size in laboratory learning is critical to student learning, and there is a need to distribute students with a natural aptitude to practical learning across the groups to promote peer learning [26]. Ensuring that students have a deeper understanding of the theory and practice will help graduates to have a successful transition to the workplace and have the skills to synthesize new information and adapt to technological changes**.** A recent study, ‘Engineering undergraduates’ [27], has shown that undergraduates have technical knowledge on joining a workplace environment, but don't understand how to communicate sufficient information about problems or to adapt their knowledge to solve workplace problems.

There is a gap in the current literature with regard as to how to develop and assess engineering learning in laboratories that specifically demonstrates relevance to postgraduate employments. That is, having an understanding of and being able to apply and analyse engineering in practice, and being able to communicate clearly to others how to implement engineering solutions. There is a lack of published research to investigate how laboratory learning environments are useful in aiding engineering students to achieve higher level thinking and develop their Emotional Intelligence (EI). This latter aspect is important as first year undergraduate engineers are often *" scornful of the subjectivity of the humanities and social sciences and take comfort in what they view as the purely objective nature of science and engineering, and they are bewildered or irritated if this view is contradicted by their instructors."*[28]. Engineering students typically score low on EI in comparison to their humanities peers[29], making this a key skill to be developed over the course of an engineering degree, as engineers design and develop products and solutions for people, and need to be able to communicate effectively in the workplace. Typically, strong EI skills improve the career prospects of engineering graduates [30]. Therefore the question is, how can we, as educators, best enable students to achieve higher level thinking and increase their emotional intelligence?

Research Methodology

The aim of this project was to investigate (i) the level of student learning and (ii) emotional intelligence development through laboratory learning. Different research methods are needed to measure these qualities. Quantitative data were collected using Multiple Choice Questions (MCQs) and qualitative data were gathered via semi-structured interviews. The MCQs provided statistical numerical data which were compared with the qualitative data. It was noted that MCQ design was critical to the project; each question and answer set was carefully considered to prevent answer bias [31]. The students did not receive feedback on their MCQ or interview so not to unduly influence their laboratory report efforts. The semi-structured interviews provided qualitative data with greater substance and depth [32], and proved to be a more holistic interpretation and assessment of student learning.

The quantitative and qualitative approaches were applied and analysed in parallel; this has been reported as being particularly valuable for identifying trends and bridging between the research methods [33]. A blended synthesis approach was beneficial as the research sample was small [34]. A quantifiable scheme codification was used to systematically convert qualitative data into quantitative data [33] and triangulation methods were developed that *"essentially involves cross-checking for internal consistency or reliability whilst testing the degree of external validity"* [35]. It should be noted this research did not contribute to the summative assessment of the students, and therefore was "risk-free" for the student participants. In addition, the validity of the design of each research method was considered, as humans may unintentionally manipulate their own answers due to cognitive reasoning [36].

Volunteers from the first year MEng/BEng Aerospace Engineering programme were sought to assess their understanding and level of learning of a theoretical topic from a lecture programme and associated practical learning opportunities to place the theory in practice. The research methods were designed not only to measure the subjects' knowledge in the specific area they were being taught, but also their (engineering) critical thinking [37]. As the project involves human subject approval, the research project adhered to the highest ethical standards throughout the project, and ethical approval was sought from and given by the faculty.

In addition the academic who developed the practical laboratory and led the practical sessions was interviewed.

The Laboratory Experience

In this paper, we define the “laboratory experience” as consisting of a lecture followed by a laboratory experiment followed by the submission of a written report for summative assessment. The topic chosen was Aerodynamic Principles with a series of experimental readings taken using an aerofoil in a wind tunnel. A total of 14 students from the cohort of 64 participated in this study. Marks for the formally assessed report were compared to the MCQ/interview grades achieved by the same student. This additional information enabled the researchers to triangulate the student’s performance in the module with their MCQ or/and interview performance. This triangulation was completed by another academic in order to ensure student MCQ/interview grades remained anonymous to both the academic leading the module and student researcher conducting the research. Between 8 and 14 students were scheduled to participate in each 2h experimental session.

Practical Experiment

The practical laboratory in the wind tunnel aimed to deliver the following learning outcomes:

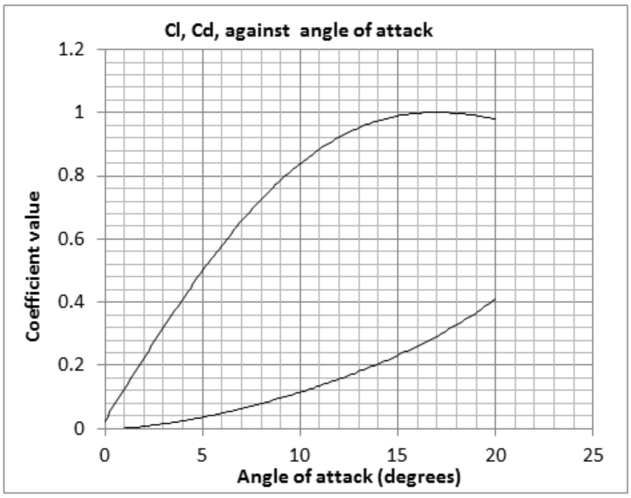
- the ability to derive velocity from pressure measurements.
- an understanding of how lift and drag coefficients vary with angle of attack of an aerofoil.
- an appreciation of the best glide ratio.
- an understanding of pressure distribution over an aerofoil in different flight states.

The MCQs and semi-structured interviews were designed to measure the student's understanding in these areas, as well as areas the subject encroaches upon, for example the application of Bernoulli's principle. This principle is a fundamental for understanding pressure distribution and the generation of lift during flight as well as general formulae used to calculate velocity from pressure measurements. The interviews were designed to see how the students respond to a change in data and the possible causes of the change; testing the student's (engineering) critical analysis skills. An example of a MCQ used after the practical part of the laboratory experience is shown in **Error! Reference source not found.**. In the case of the semi-structured interviews, the questions put to the students were scenario-based questions, and students were asked to elaborate on points to show their depth of understanding on each individual area, an example of semi-structure interview question is shown in **Error! Reference source not found.**. In addition students were asked about their impression (reflections) of the practical laboratory learning experience.

Figure 1. *Example of MCQ used in this Research*

7. Attached is the data gathered from a wind tunnel experiment showing the coefficient of Lift and Drag against the angle of attack. At what point is the aerofoil experiencing its highest 'aerodynamic efficiency'?

a) 6 degrees
b) 10 degrees
c) 14 degrees
d) 18 degrees



In the case of the semi-structured interviews, the questions put to the students were scenario-based questions, and students were asked to elaborate on points to show their depth of understanding on each individual topic. An example of a semi-structure interview question is given in **Error! Reference source not found.**. In addition students were asked to reflect on their practical laboratory learning.

Figure 2. *Example of Semi-structured Interview Question*

Your friend has asked you to help him create a simple model aircraft and he is struggling to understand the basic principles behind flight. How would you explain the basic aerodynamic forces acting on an aircraft to him?

Results and Discussion

Data Collection

MCQ Data Collection

Once a MCQ was completed by a student, it was given a grade (percentage of correct answers) by the student researcher.

Semi-Structured Interviews

Each interview was audio recorded, the interviewer also made written notes. Each interview lasted approximately 20 minutes in length of time. In order to effectively map the responses from each interview, the student's responses were graded by the interviewer using the 'grading sheet' shown in **Error! Reference source not found.**. The students were graded 1 to 6 (in increments of 0.5) on their 'level of understanding' as judged by the researcher. The grading sheets were completed after each interview.

Table 1. *Semi-structured Interview Quantitative Grading Sheet*

Participant Number (X):	
Scenario	Level of understanding
1 Basic aerodynamic forces	1-6
2 Analysis of aerodynamic performance	1-6
3 Interpreting graphical data	1-6
4 Understanding of advanced aerodynamics	1-6
Notes	

The level of understanding was quantified using the assessment rubric given in Table 2. The assessment rubric was developed to assess how well the student met the practical experiment learning objectives as well as Bloom's Taxonomy of learning [2], therefore the students were graded on their:

- knowledge in the subject
- ability to analyse
- ability to evaluate information

This methodology provided quantified data that could be compared with the results of the written lab report. The grades were averaged to find each student average level of understanding of the learning from the laboratory.

Table 2. *Semi-structured Interview Quantitative Grading Sheet Criteria*

Level of understanding	Description
1 <16.7%	No understanding of the subject
2 16.7%-33.3%	Shows limited knowledge of the subject, no understanding of engineering applications of that knowledge.
3 33.3%-50%	Shows a basic knowledge in the subject, has limited knowledge of alternative engineering applications.
4 50%-66.7%	A good knowledge in the subject, showing limited critical thinking in engineering principles.
5 66.7%-83.3%	A strong knowledge of the subject, can apply knowledge to other less familiar engineering scenarios.
6 83.3%<	A full understanding of the engineering principles involved, show's an in depth knowledge and shows critical thinking of all engineering principles.

Results and Discussion

Of the total of 14 students who volunteered to support this study, 9 students completed the MCQs immediately after completing the laboratory work and 8 students participated in the semi-structured interviews. Table 3 illustrates the assessment grades for the 14 participants alongside the results of the MCQ and/or semi-structured interview. Unfortunately three of the participating students subsequently decided to withdraw from the course and did not submit a lab report for assessment. If a participant number is red, the student failed to submit a report and has since withdrawn from the course after completing the MCQ/semi-structured interview. Comparison of the semi-structured interview grades with the MCQ grades shows that numbers agree to ±10%. The sample size is too small to draw statistically valid quantifiable conclusions, but can inform on a qualitative basis. Comparison of the MCQ results with the report grades yielded a mean difference of ±3.62%, with no difference exceeding 6%. The majority of students demonstrated a slight improvement in their level of understanding by the time the report was submitted, but this may simply be a function of the differing assessment technique. Comparison of the report and semi-structured interview grades yields an average difference of ±4.63%, with a maximum difference of 10.5%. The majority of students demonstrated less learning in the report than in the semi-structured interview. This finding suggests either that reflection during the interview enabled students to show their true depth of learning more accurately, or that the academic writing skills of first year students are less developed than their verbal skills. This finding is consistent with research into different modes of assessment in New Zealand [38].

Table 3. *Comparison of Quantified Results Assessed by MQC, Semi-structured Interview and Written Report*

Participant number	Written Report Grade	MCQ result	Semi Structured interview result	Difference between MCQ and report	Difference between semi-structured interview and report	Difference between MCQ and semi-structured interview
1	75	73.3	79	1.70%	-4.00%	5.7%
2	65	60	60.4	5.00%	4.60%	0.4%
3	29	N/A	33.3	N/A	-4.30%	N/A
4	48	N/A	54.3	N/A	-6.30%	N/A
5	73	N/A	79	N/A	-6.00%	N/A
6	52	N/A	62.5	N/A	-10.50%	N/A
7	51	N/A	52	N/A	-1.00%	N/A
8	0	40	65.3	N/A	N/A	25.4%
9	0	66.67	N/A	N/A	N/A	N/A
10	65	66.67	N/A	-1.67%	N/A	N/A
11	70	73.3	N/A	-3.30%	N/A	N/A
12	0	53.3	N/A	N/A	N/A	N/A
13	59	53.3	N/A	5.70%	N/A	N/A
14	71	66.67	N/A	4.33%	N/A	N/A

The results of this study indicate that the students may be marginally under-performing in the written report relative to their ability and understanding. The report writing is intended to provide the students with an opportunity to link the theory with practice, and to reflect in a critical manner [27]. It is also intended as the first step in the process of developing the students' report writing skills in preparation for employment as professional engineers. A report template (framework) was provided by the academic to help the first year students to develop their in-depth report writing skills. The results indicate further refinement of the framework is required to support the students further in developing their skills to contextualise their understanding in the written format.

Semi-structured Interview with the Aerospace Engineering Lecturer

The academic (lecturer) was impressed at the level and breadth of the MCQ and found them to be a true representation of the level and breadth of learning expected to be developed during the laboratory experience. The academic was impressed that the student MCQ results correlated to the student reports. The MCQ were a true representation of the level learning they need to show in the report. However, despite the MCQ having potential as a method to assess the student laboratory learning, the academic felt that it is important to develop laboratory report writing skills in preparation for writing formal reports in later years. The academic mentioned that an extended report, "*forces them [the students] to put the fundamentals into* *context in their writing and think about the fundamentals; to show their understanding of the fundamentals which they cannot show in a short write up*".

The academic reflected that the practical experiment would be better suited to a class size of less than 10 students (the current assigned capacity of the room). With 10 students, only five students are able to volunteer to interact with the equipment, and the remaining five students observe. Typically, half of the observing students in each practical disengage from the laboratory learning: *"I try to get the students to look at the data as it develops… there are 2-3 [students]… don't really take part".* The observing students potentially are missing out on the learning opportunity. The academic would welcome class sizes small enough to permit all students to have an active role in the practical, but it *"would not be feasible to break up into smaller groups"* due to resource limitations.

No student said that they would prefer to be taught in smaller groups. Significantly, 57% of all students interviewed stated that they would prefer more time in laboratories. Further research needs to be understand how to optimize the use of practical experiment time: would students benefit more from shorter, interactive and intense practical sessions, or is more time spent in an experimental environment, albeit sometimes in a passive role, more conducive to long-term advances in understanding?

The academic thinks the learning could be improved in this level 4 laboratory experiences using less hands-on methods, as some of the theory is complex and is revisited in greater depth in the second year of the course. At level 4, the foundations of understanding of aerodynamic principles need to be developed. One of the aims of the practical session is to introduce students to the wind tunnel equipment and computer data acquisition systems, extracting and manipulating data from the system in preparation for the rest of the course. The laboratory experience is timed to act as a revision aid of the theory studied earlier in the year. The academic also intends the laboratory exercise to develop more encompassing skills in the students in how to use the technology in the laboratory to extract, manipulate and analyse the measured data from the equipment in an excel spreadsheet. The academic doesn't think changing the laboratory designs to a simpler experiment would be advantageous for student learning as the current laboratory design acts as a revision tool for level 4 semester 1 subject learning. Recent revisions to the module this year have already provided one additional laboratory, increased contact time and supported learning in the laboratory experiences, and a report template with supporting rubric and the initial results indicate anecdotally a positive impact on the student learning in comparison to previous years. The academic highlighted that not all learning is suited to be deepened in a laboratory setting, *"I am not a fan of taking away lecture and tutorial [time] for laboratories"*. This particular laboratory experience is more of a demonstration of the theory in practice, and provides a framework to support student learning by putting the subject fundamentals into context. It is a question of the academic's personal choice of teaching style to support their students, as *"no one size fits all"* meaning that it should be dependent on the lecturer and the laboratory at hand. Therefore the role of the academic is important in the planning of the learning activities [39] and ensuring learning consistency in the laboratory.

Student Reflections

The semi-structured interviews with first year undergraduates also recorded the students' reflections of the learning experience in the laboratory. The main points gathered from the reflective qualitative data were:

- Laboratory experiments were seen as a positive learning experience. *"[Aerodynamic Laboratory] Most interesting lab so far*" Student No 1.
- Students wanted more time doing practical work in the laboratory learning environment.
- The majority of participants showed a strong understanding of the role of the laboratory.
- Participants believed their learning increased with writing laboratory reports as part of the laboratory experience.[1]
- Half of the students involved were happy with the current structure used, as one student highlighted it supported their learning approach, *"[The] purpose of the lab session [is to] visualise the mathematics that we have been studying for the last 9 weeks or so. I would not change it;, it is how I like to be taught*," Student No 7.
- The rest of the students expressed a preference for a change in structure; the most common comment was a desire for an increase in the number of laboratory experiments.

The qualitative data gathered through semi-structured interviews demonstrated that students felt that the present structure of the laboratory experience worked well and they were *"currently happy with it"*. One student believed that more lectures on a topic prior to the laboratory practical were needed to enable students to gain a greater knowledge of what experimental results to look for during the experiment. It should be noted that 75% of students in this laboratory experience showed a strong understanding of how important a laboratory was to their engineering learning, with students saying that it gives them a *"deeper understanding of what you've been doing (studying) in lectures"*. This demonstrated that a majority of students are developing EI of how to interpret their engineering education. However, further research is required to investigate the development of EI in practical learning. As the development of student EI through work-based/related learning has the potential to be translated into for work-based practice [30].

[1] Pedagogically this would be considered true as the role of the experiment (whether simulation or practical) and written report is to move the learner through all four quadrants of Kolb's learning theory, [40]. The laboratory provides the opportunity to apply the theory into practice, the writing of a report provides the opportunity to reflect and assimilate sensible conclusions.

The students expressed the importance of having a lecture/tutorial on the topic before the practical experiment; the academic was also enthusiastic about this. The importance of having theory, related to the practical experiment prior to the laboratory is made clear by Crawley et al [27] as the laboratory should build upon the foundation of theoretical knowledge gained before the practical experiment.

Conclusions

Methodologies have been developed that allow quantification of interview data that tallies well with results from MCQ and written laboratory reports over a wide range of student ability. The interview data demonstrate that the laboratory experience has a positive effect on student learning. The academic reported that increasing the number of practical laboratories (from one to two) from his observations had had a positive effect on the student learning. The extended “laboratory experience” including lecture/tutorial, practical experiment, and training in data analysis techniques enabled the students to analyse the results and deepen their understanding of the subject. The semi-structured interviews demonstrated students were able to reflect and articulate their level of understanding, and were able to contextualise the theory using the laboratory experience. This is a key step into becoming reflective engineers [41], an EI quality. Therefore the initial qualitative results indicate that students are developing EI. Further research is required to understand the level of EI development through the laboratory experience as students advance through their degree. However, the first year students would benefit from the laboratory report writing scaffolding being further refined to enable and support them to demonstrate their:

- level of understanding
- ability to critical analysis the results
- ability to place the results in context to the theory
- reflections on the learning

Adopting such approach has been shown to improve first year science students' ability to write more accomplished laboratory reports, and develop cognitive learning strategies from practical laboratories [42].

The qualitative research with the academic identified that the laboratory experience was timed to consolidate the accumulated theoretical learning of the student from a series of lectures and tutorials. How effective this has been will not be fully apparently until the end-of-module examination results are known. The quantitative and qualitative results support the evidence that the practical laboratories and written report are achieving their objectives of enabling the students to place the subject’s fundamentals in context and acting as a revision aid of the learning from the lectures and tutorials. However, there is an opportunity to improve further the laboratory design to enable the active engagement of all ten students with the laboratory practical element, as opposed to the current design of five students "doing" and five students "observing".

The students expressed the view that they wanted more time in the laboratories. The academic was also given a voice through this study, and highlighted a preference for additional contact time, via laboratory preparation sessions, and smaller and more frequent laboratory sessions. However from the academic's perspective, additional laboratories should not be at the expense of lecture and or tutorial time.

The approach to designing engineering laboratory experiences needs to be adaptable to change, as emphasised by the academic, trusting academics to use their own pedagogical judgement to decide what the aims and outcomes of each laboratory experience should be, whether this is reflecting on theory learned in lectures, applying theory in practice or developing technical skills. Therefore, lecturers would need access to an increase in the resources available allowing them more contact time in the way of laboratory experiments. This in turn means universities would need to consider implications of how to use resources in order to allow more laboratories, with fewer students per laboratory, thus increasing the engagement.

The content of the laboratory experiment will need to be considered, as some topics may not need the same level of increased detail and laboratory time. The research with the academic suggested that the module leader needs to be free to make an academic judgment to determine the timing, length and number of laboratories required.

Each engineering module needs careful consideration to achieve the optimum balance of time allocated to lectures, tutorials and laboratory experiences and independent learning. Creative thought should be given to how to address it; this may involve side investment, using flipped classrooms to intensify the theoretical learning [43], or requiring students to develop supplementary learning materials to support the theoretical learning [44], liberating the academic to support more practical laboratory experiences. The key is in the planning of the teaching process - lecture/ tutorial/laboratory - and a clearly defined set of learning outcomes for each learning opportunity that supports the development of EI and learner autonomy as the course progresses.

Future Work

There is a need to investigate the potential of alternative methods of teaching and teaching resources, e.g. flipped classrooms or supplementary instruction (web-based or classroom) to maximize the effectiveness of the laboratory learning environment.

There is also a need to measure the effects of increased time spent in the laboratory to determine whether the diversion of resources to this activity at the expense of time spent in seminars is beneficial. Specific laboratory experiments could be used to validate this; with engineering students as voluntary participants on an alternative engineering course (such as mechanical engineering), in order to have the compatible skills without the knowledge on the specific subject.

The academic laboratory write up template requires further refinement to assist the first year students in writing in-depth laboratory reports and in communicating their metacognitive development as a result of the laboratory experience.

Another area worthy of more study is the development of EI (within and without the laboratory experience) as engineering students progress up the academic levels.

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