What are students learning in practicals? A cross sectional study in university physics laboratories

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New South Wales 2006
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Abstract: *A primary objective of teaching in laboratories is for students to understand the purpose and procedures for undertaking an experiment, an essential element of the scientific method. However, it is difficult to evaluate this aspect of learning in laboratories. For example, does the approach taken by second year students differ from third year students? We have investigated such questions in a research focused Australian university. A random sample of 46 second year and 16 third year students were given a simple open-ended activity. We found that there is a difference in the demonstrated levels of experimental sophistication between second and third year students. Furthermore, a comparison of the academic achievement of the best two levels of experimental sophistication showed a difference. On the whole students performed better than expected and most demonstrated an understanding of procedures and processes of experimentation. We propose that this is due to the local context of our curriculum where students have had experience in open ended experiments. We discuss issues such as self selection and time lag in learning. There is no doubt that teaching and learning in laboratories is a complex process, this study considers overall approaches taken by students when given a choice.*

Introduction

The motivation for this study was to assess whether the student learning outcomes are being achieved for undergraduate laboratory teaching. The study is timely since the student body, employer demands, and competing demands on student learning time (contact hours) are changing. However, relevance and importance of experimental work has not changed and still occupies a central role in the physical sciences. The following sentiment by Nobel Laureate Richard Feynman encapsulates the significance of experimentation in the sciences.

> The principle of science, the definition, almost, is the following: The test of all knowledge is experiment. Experiment is the sole judge of scientific 'truth'.
>
> Feynman, 1963, Lectures in Physics, 1-1.

In this study, students were assigned a task, without any instructions on how it should be carried out. The onus was on the students to plan their approach, collect and process data, present results and discuss sources of experimental error. The aims of this study were to address three questions:

1. What are the levels of experimental sophistication amongst second and third year university physics students?
2. Is there a significant difference between the distributions of students in second and third year showing the varying levels of experimental sophistication?
3. Does the level of experimental sophistication relate to academic performance of students in formal examinations?

The laboratory skills necessary to carry out the experiment are not specific to physics (Van Hecke, Karukstis, Haskell, McFadden and Wettack 2002). Science students have been exposed to various aspects since high school and are expected to progressively become proficient in them. We expect students with one year of exposure to tertiary laboratory environment to demonstrate understandings of skills such as basic error analysis, and students with additional exposure to be more proficient in the more challenging areas of analysis.

Trends and issues in laboratory teaching

Traditionally, laboratory work supports the teaching and learning of undergraduate science in higher education (Khoon and Othman 2004). The justifications for doing so are many. Some prime reasons are as follows:

- there are some basic skills that students of a science domain must have – using microscopes for biology, using pipettes for chemistry and construction of circuits for physics.;
- laboratory experiments demonstrate concepts and aid with learning content; and
- knowledge generation in the sciences is through a cyclic process between experimentation and theoretical modelling hence students need to do experiments to understand this scientific method.

These and other justifications are embedded in the objectives of most laboratory programmes. General goals of science laboratories are outlined in studies such as Boud (1973); Lazarowitz and Tamir (1994) and Millar and Driver (1987). The physics perspectives on goals of undergraduate laboratories are discussed in AAPT (1997) and Reif and St John (1979). The aims of laboratories often reflect the attitudes and experiences of teachers (Swain, Monk and Johnson 1999). Trumper (2003) raised the issue of educators needing to be selective in choosing goals; focusing on laboratory skills such as observations and testing of hypothesis or experimental technique and error analysis. On the broader issue of curriculum design, Lubben, Buffler, Campbell and Allie (2001) proposed shifting students from using point to set reasoning, where the former refers to using individual data points and the later to repeated measurements and scatter in data.

Recently, we noticed three trends. First, the introduction in the laboratories of computer based activities (Salumbides, Maristela, Uy and Karremans 2002). ‘Dry labs’ using computer simulations can be cheap and quicker than regular practicals, allowing teachers to do more, and students the opportunity to explore concepts themselves. The result is that ‘hands-on’ work is not ‘hands-on equipment’; it is simulated (Thacker 2003). At the same time computers have been used as technology for enhancing experimental work as described in Cheary, Gosper, Hazel and Kirkup (1995). Second, the reduction of time spent in laboratories to allow time for other learning activities. Both these trends have been documented for the Australian physics context (Sharma, Mills, Mendez and Pollard 2005, 40-42). Third, pedagogy researchers are investigating student learning in areas such as interactive lectures (Hake 1998; Sharma, Khachan, Chan and O’Byrne 2005) and tutorials (Sharma, Mendez and O’Byrne 2005); resulting in less research on experimental laboratories. Hence, there are not enough understandings of how students of the current century learn in experimental laboratories. In a review of teaching in science laboratories two decades ago, Hofstein and Lunetta (1982) echoed similar sentiments. The question then arises, to what extent do students acquire understandings of the scientific method and basic skills in the context of the changing role of undergraduate experimental laboratories. Assessing such laboratory skills is a challenge in itself. We note the discussion on a national effort to assess learning in science laboratories in Ireland (Bennett 2001, Kennedy and Bennett 2005). Harlen (1999) argues that focussing classes on theory further limits the ability to assess laboratory skills. It is to answer questions such as these that we undertook a study to look at teamwork, competency in dc circuits and the levels of experimental sophistication of students in undergraduate physics laboratories. In this paper we report on the later.

Theoretical perspective

The authors are participant observers in this study with JK and MDS coordinating third and second year laboratories at the time of this study, and AR an experienced tutor. As coordinators of laboratory programmes constrained by the culture of a research focussed department, we have taken the opportunity to explore student learning with the intent of improving instruction and learning outcomes.

The research process has been conceptualised using the framework described by Crotty (1998). The theoretical perspective of our study is post-positivism whereby we explore student experiences of experimental laboratories in a quantitative manner (Clark 1998). The study design is quasi experimental within an authentic educational setting. The data collected is quantitative and we use statistical analysis. However, some variables and their exploration were not predefined. As our understandings progressed, new ways of investigating the data emerged, underpinning the exploratory nature of the study. Being physicists, quantitative exploration of the data has emerged as predominant and the most comfortable. Qualitative studies would be invaluable in understanding aspects such as how students of different genders interact with equipment and how students work in groups.

Method

The study sample

Mainstream first year physics courses at the School of Physics, University of Sydney consist of 30 hours of laboratory work per semester. In first semester half the time is dedicated to mechanics experiments followed by experiments on waves. In second semester the first half is dedicated to circuit experiments followed by open-ended experimental projects. The projects involve students devising and undertaking an investigation into a physical phenomenon of their choosing such as those described by Hegarty (1978) and Marshall (2002). Second year students participate in 12 three hourly laboratory sessions in each semester. In first year laboratories, students work in teams of three and in second year in pairs, not individually as noted by Cox and Junkin (2002).

The study was carried out during the first laboratory sessions of second year and third year physics. Consequently, the difference between the groups was 72 hours of experimental physics experience. The precise question students were asked to deal with is covered in high school curricula and none of the students would have encountered it in university physics laboratories at this institution.

A random sample of 46 second and 16 third year students were selected from the 2005 cohorts enrolled in the laboratory classes. The students participated with informed consent and were aware that the study would not contribute towards their final mark. For the second year cohort, academic results for first year physics courses were obtained.

Choice of question

The question was selected on the basis of the relative simplicity of the measurements, while offering students opportunities to demonstrate their understanding of experimentation. Each student was provided with a pendulum, stopwatch, ruler and graph paper, and given two hours to answer the following question.

A precise measurement of the acceleration due to gravity

For small angles, the period of oscillation of a pendulum is given by

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where l = length of the pendulum and g = acceleration due to gravity

1. Using the equipment on the bench devise an experiment to obtain a precise value for the acceleration due to gravity.
2. Carry out the experiment using the skills you have learnt in your physics labs so far. Record all data as you would in a formal logbook in a research lab.
3. Analyse the data to obtain a precise value of the acceleration due to gravity.
4. Write your measured value of the acceleration due to gravity as you would report to a scientific audience.

Comments on methodological issues

This study has been carried out in an authentic educational setting, bringing its package of strengths and unanticipated challenges. First the challenges: the second year class size was 120, out of which 115 were present on the day and 46 were randomly selected for this study, the remainder did another study. The sampling process was adequate for capturing the diversity of the second year population. However, the third year class size was 80 and only 36 students were present, from which 16 were randomly selected for this study. This was due to increased flexibility in subjects and allowing third year students to negotiate timetables with departments. Hence students were sorting timetables when we were carrying out this study. From experience we are confident that this does not introduce a systematic bias as the timetable issue affects students across the board and not a particular group of students. The authors have perused indicators such as degrees enrolled in and performance to confirm that we have a random sample of 16 students who are representative of the class. The strength of the study was that the authentic setting provided a measure that reflected teaching and learning practices and its outcomes, results that the School can seriously consider when making decisions about curriculum.

Three second year students and one third year student recorded bare minimum and were excluded, bringing the sample size to 43 for second year and 15 for third year. No marks or rewards were available for participation because we wanted to capture what students would do spontaneously, without preparation and without examination conditions – the ingrained experimental principles (such as that in Campbell, Kaunda, Allie, Buffler and Lubben 2000).

The study was conducted on four afternoons in the first week of semester and AR ensured that the equipment was identical for all students. Apart from the authors, two additional trained tutors supervised the sessions. When using t-tests to compare means the relevant data were tested for normality using residuals. One outlying point, more than two standard deviations away from the mean, was removed for tests assuming normal data.

Analysis and results

Categorisation of student responses

The levels of experimental sophistication demonstrated by students and the criteria for differentiating the steps undertaken by students were not predetermined. Rather they emerged from the data through a process of iterative categorisation as shown in Table 1. In the first stage, each author examined student responses, independently arriving at similar categories representing the levels of experimental sophistication. In a subsequent meeting we developed clear definitions of three levels of experimental sophistication.

Table 1. Development of levels of experimental sophistication and criteria for differentiating the steps undertaken by students

Stage	Sample	Activity	Conducted by
1	2nd year, 3rd year	Finding the levels of experimental sophistication	AR, MDS, JK
2	3rd year	Developing binary criteria	AR, MDS, JK
3	3rd year	Grouping criteria	AR
4	2nd year	Individual comparisons and iterative refinement of criteria	AR, MDS
5	3rd year	Individual comparisons	AR, JK

In stage two, third year student responses were used for developing a binary criteria for differentiating the steps undertaken by students. The third year papers were chosen since they represented more diverse ‘correct’ details. A thorough examination of the papers was carried out to determine each step used by students, resulting in a list of unique steps. The list was used to develop a comprehensive criteria for differentiating the steps undertaken by students.

The third stage of our analysis involved closer examination of the list of unique steps to determine those that belong only to a level of experimental sophistication and those that are common across the three levels.

The authors then used these criteria to compare the second year papers independently, which we label as stage four of the project. Two of us (AR and MDS) compared the second year papers individually then discussed discrepancies and contentious issues to refine the criteria.

Two of us (AR and JK) then applied the refined criteria to the third year responses, finding no further discrepancies in stage 5.

The levels of experimental sophistication

The levels of experimental sophistication are shown in Table 2 and the hierarchy is justified as follows.

- Graphical analysis is the most sophisticated as it allows the experimenter to visualise trends and scatter in the data, and to identify outliers. It indicates a deep understanding of relationships and how they are explored in experimentation.
- The analysis of multiple values of g is the next sophisticated approach as it allows the experimenter to assess the scatter in the value of g.
- The lowest level of sophistication is in calculating a single value of g from multiple values of the period T. It is difficult to identify outliers and evaluate if the calculated g is reasonable.

Table 2. Definition and ranking of levels of experimental sophistication

Category	Rank	Description
Graphical approach	1	Drawing a graph of T^2 vs. l, and determining g from the line of best fit.
Multiple g approach	2	Recording multiple values of T and for each of these calculating a value for g. Determining mean g.
Multiple T approach	3	Recording one or more values of T and determining a mean T. Calculating a single value for g using mean T.

The criteria for differentiating the steps undertaken by students are shown in Table 3. Criteria 1–10 and 15–21 are common to all three levels of experimental sophistication, while criteria 11 to 14 are unique to each level.

Table 3a. Abbreviated criteria for differentiating the steps undertaken by students. Only criteria common to all approaches are listed.

Number	**Description of Criteria**	**2nd Year**	**3rd Year**
1	Coherent and formal statement of aim.	60%	93%
2	Statement of formulae and its interpretation.	100%	100%
3	Description of experimental procedure.	93%	100%
4	Describing of analysis before commencing the experiment - planned analysis.	30%	27%
5	Presence of an appropriate diagram.	53%	40%
6	Prediction or outline of possible systemic errors in equipment or setup.	16%	13%
7	Presentation of data in appropriate and labelled tables.	86%	93%
8	Measurement of period for multiple lengths. Essential for graphical analysis.	60%	80%
9	Measurement of more than one set of readings for each length.	74%	93%
10	Measurement of multiple swings for each reading.	84%	100%
11-14	*Specific to approach*	-	-
15	An acceleration due to gravity within ±0.8ms^{-2} of the accepted value providing an overall indication of the quality of the experiment.	86%	84%
16	Coherent and formal statement of conclusion.	84%	93%
17	Formal statement of uncertainty 'g±...' regardless of accuracy.	19%	40%
18	Comparison with accepted value of acceleration due to gravity 9.8ms^{-2}.	51%	53%
19	Comment upon specific uncertainties, ways to improve the experiment.	42%	53%
20	Use of correct and consistent units.	74%	100%
21	Use of correct and consistent significant figures.	37%	27%

Table 3b. Abbreviated criteria 11 to 14 for the graphical approach

Number	Description of Criteria	2nd Year	3rd Year
1-10	*See above*	*See above*	*See above*
11	Graph with a reasonable line of best fit (LBF) - utility of a linear trend.	100%	100%
12	Graph with a reasonable line of worst fit (LWF).	17%	25%
13	Plotting of multiple period values or error bars.	17%	25%
14	Determination of uncertainty – variability in experimental results.	25%	38%
15-21	*See above*	*See above*	*See above*

Table 3c. Abbreviated criteria 11 to 14 for the multiple *g* approach

Number	Description of Criteria	2nd Year	3rd Year
1-10	*See above*	*See above*	*See above*
11	Determination of *g* for each measurement – multiple measurements at different lengths essential.	100%	100%
12	Determination of a mean *g*.	100%	80%
13	Determination of standard error (SEM) or standard deviation (SD) of *g*.	0%	20%
14	Determination of uncertainty in *g*. Markers were lenient with correctness.	8%	20%
15-21	*See above*	*See above*	*See above*

Table 3d. Abbreviated criteria 11 to 14 for multiple *T* (period) approach

Number	Description of Criteria	2nd Year	3rd Year
1-10	*See above*	*See above*	-
11	Calculation of single period, or mean period from periods for each length.	89%	-
12	Determination of SEM or SD of period.	17%	-
13	Determination of *g* using mean period.	89%	-
14	Determination of uncertainty in *g*. Markers were lenient with correctness.	11%	-
15-21	*See above*	*See above*	-

Distributions of levels of experimental sophistication

Once the relative degrees of sophistication had been decided, and the second and third year responses categorised, it was possible to compare the proportions of students from each cohort choosing to use the different levels of sophistication and determine if the relative distributions were from the same population. Table 4 shows the numbers of students from each year that chose the different levels of experimental sophistication.

Students in the third year cohort tended to favour more sophisticated analysis techniques than those in the second year cohort. A chi-squared test can be used to test if there is a statistically significant difference. However, because of the small numbers we will need to combine multiple *g* and multiple *T* approaches for each year. Once this combination is done it is obvious that there is a difference in distributions (χ^2 (df=2, n=58) = 6.44, p <0.05). That is, a larger fraction of third year students employ the more sophisticated approach.

A fraction of the second year students choose to not major in physics, consequently a self selected group of students continue into third year physics. The self selection could be due to reasons such as poor achievement, perception of poor performance, lack of confidence/interest or simply the availability of attractive alternative options.

Table 4. Numbers of students using the different levels of experimental sophistication within each year cohort

	Levels of Experimental Sophistication		
	1	2	3
Number of 2nd year students	12 (28%)	13 (30%)	18 (42%)
Number of 3rd year students	8 (53%)	5 (33%)	2 (13%)

Table 5. Levels of experimental sophistication vs. first year examination marks for the second year cohort, with standard error of mean (SE).

Levels of experimental sophistication	n	Mean examination mark (%)	SE
1	11	68.5	4.1
2	12	56.0	2.3
3	16	64.3	4.5

A detailed study of what students had done for each criterion was carried out. Statistical analysis of each criterion was ruled out as this was not the objective of the study and hence data had not been collected to allow such analysis. If students have been doing laboratory work for some time during their education and are becoming increasingly proficient, then we would expect them to be competent in most criteria. To understand this we examined what students had written for each criterion. The expectation in criterion 4 was for students to provide a thorough plan of their procedure and data analysis. About a third of the students did so. In a similar manner, the expectation in criterion 6 was for students to explore systematic errors and flaws, and about 15% of the students did so. Criteria 12, 13, 14, 17 relate to graphical analysis and propagation of uncertainties, a skill that was not demonstrated particularly well. Similarly, the expectations in criterion 18 and 21 were not handled well. A persistent concern amongst academics, the poor use of significant figures is mirrored in our study. The above mentioned criteria were the ones not handled well by most students.

We can also explore the criteria that stand out from the others. For criterion 21, there is a reduction from 37% in second year to 27% for third year. Furthermore the overall percentage in both years is low for this criterion. As mentioned above, both groups of students are not taking adequate note of significant figures and indeed the skill appears to deteriorate. We note that very few second year students (19%) satisfy criterion 17 suggesting that the students are not accustomed to writing their final results in the appropriate form. There are no second year students who adequately used statistical methods. Whether they understand what these are and where to use them is left for further research.

On the whole though, more third year students were able to demonstrate that they were competent than second year students. It is not clear from this study whether students would have given more attention to these criteria if the task contributed to summative assessment.

Comparison of the level of experimental sophistication with academic results for the second year cohort

The examination results from first year were considered indicative of second year students' academic performance. Assignment and laboratory marks were not considered since these tasks were assessed in teams of three.

The number of second year students (for whom first year academic results were available) in each level of experimental sophistication and their mean examination marks are given in Table 5. A two sided *t*-test of the difference in the mean examination mark of students who chose the highest and second highest levels of experimental sophistication (null hypothesis of no difference) shows a statistically significant difference ($t = 2.69$, $df = 21$, $n = 23$, $p<0.05$, unequal variances assumed). No other statistically significant results were obtained. It is not clear why the level three students have a higher mean examination mark than the level 2 students. It is perhaps indicative that laboratory classes present a complex learning environment that has elements that some students do not encounter in normal lecture style course work.

Discussion

Although, on average, we found that students were able to use scientific methods and processes (statement of objective, statement of procedure, confidence of results and drawing valid conclusions), they employed widely varying levels of sophistication. We developed three levels of sophistication from their responses. In particular, there was a statistically significant difference between the level of experimental sophistication chosen by second and third year students, where third year students used more sophisticated approaches. However we cannot discount self selection and we note that the third year sample was representative but small.

One might expect that higher year students would have matured to understand the importance of more sophisticated methods and therefore the results are not surprising. However, it is worth noting that the highest level of experimental sophistication is emphasized in the first year laboratory classes and, consequently, one might expect that most of the second year students to have adopted it. As a result, the improved level of sophistication by third year might also be due to the repetition of the importance of the highest level of sophistication during second year. Consequently, this stresses the role of repetition and time lag in student learning, as noted by Roth and Roychoudhury (1993).

It was found that there was a correlation between the level of sophistication chosen by second year students and their examination results from the previous year. Students with more sophisticated approaches scored higher in their exams. Although this may not be surprising, there is a common and anecdotal belief that the abilities of students in laboratory classes are not connected to their performance in lecture material examinations. We find that in general this is not true.

Implications for future research and practice

We found that literature on the teaching and learning in experimental laboratories was lacking, particularly in higher years of university studies. Furthermore, the suggestions and recommendations made by Hofstein and Lunetta (1982) are still pertinent. Are students in our sample different to those in other reported studies? The major difference was that students in our study were consistently using multiple readings and scatter in the data, an understanding found to be lacking in studies such as those by Lubben et al. (2001). The idea of exploring levels of experimental sophistication, is one that could be fruitful in assessing skills learnt during research-based and open-ended experimental projects.

By far the most important implication for practice at our institution is that the effort and resources invested in experimental physics laboratories and open-ended experimental projects is of value to student learning. On the other hand, the projects need to be systematically studied. Furthermore, the use of pedagogically sound strategies such the use of flow charts advocated by Davidowitz, Rollnick and Fakudze (2005) have the potential for enhancing the laboratory programme. More broadly, repetition and time lag are important for effective learning in the laboratories and need investment of student time, which is increasingly being depleted by competing demands.

Conclusion

In this study we asked second and third year students in their first week to carry out an experiment, without their prior knowledge that this was going to be asked of them. Although the theory and equipment were supplied, the students were expected to individually plan and execute the experiment, and record their results within two hours. The experiment was to measure the acceleration due to gravity using a pendulum. This is one of the well established classical physics experiments and would have been familiar to most university physics students from high school studies. The individual approach to experiment was particularly relevant since all of our first year physics students work in groups. Our interest was to determine the individual level of experimental competency that these students acquire as a result of this group work.

One can say that, overall, students have learnt the basic structure of scientific reporting and analysis (all be it with different levels of sophistication), which is a skill not specific to the study of physics but one that is common to all senior tertiary level science students. We believe that opened-ended experimental projects at our institution have helped in enforcing the scientific method of reporting experiments. We are currently using the outcomes of this work to change the laboratory learning experience in order to emphasis the individual learning skills while maintaining the team approach.

References

AAPT (1997) American Association of Physics Teachers, goals of the introductory physics laboratory. *The Physics Teacher*, **35**, 546–548.

Boud, D.J. (1973) The laboratory aims questionnaire – a new method for course improvement? *Higher Education*, **2**, 81–94.

Bennett, J. (2001) Practical work at the upper high school level: the evaluation of a new model of assessment. *International Journal of Science Education*, **23**, 97–110.

Campbell, B., Kaunda, L., Allie, S., Buffler, A. and Lubben, F. (2000) The communication of laboratory investigations by university entrants. *Journal of Research in Science Teaching*, **37**, 839–53.

Cheary, R., Gosper, M., Hazel, E. and Kirkup, L. (1995) Revitalising first year physics laboratories at the University of Technology Sydney. *Australian & New Zealand Physicist*, **32**, 119–124.

Clark, A.M. (1998) The qualitative-quantitative debate: moving from positivism and confrontation to post-positivism and reconciliation. *Journal of Advanced Nursing*, **27**, 1242–1249.

Cox, A.J. and Junkin, W.F. (2002) Enhanced student learning in the introductory physics laboratory. *Physics Education*, **37**, 37–44.

Crotty, M. (1998) *The Foundations of Social Research*. Sydney, Allen & Unwin.

Davidowitz, B., Rollnick, M. and Fakudze, C. (2005) Development and application of a rubric for analysis of novice students' laboratory flow diagrams. *International Journal of Science Education*, **27**, 43–59.

Feynman, R. (1963) Lectures in Physics, 1-1.

Hake, R.R. (1998) Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, **66**, 64–74.

Harlen, W. (1999) Purposes and procedures for assessing science process skills. *Assessment in Education: Principles, Policy & Practice*, **6**, 129–144.

Hegarty, E.H. (1978) Levels of scientific enquiry in university science laboratory classes. *Research in Science Education*, **8**, 45–57.

Hofstein, A. and Lunetta, V.N. (1982) The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research*, **52**, 201–217.

Kennedy, D. and Bennett, J. (2005) Response to 'Assessment of Practical Work in Ireland: A critique' by

P. Matthews and P. McKenna. *International Journal of Science Education*, **27**, 1225–1227

Khoon, K. A. and Othman, M. (2004) Some thoughts on the introductory course in physics. *College Student Journal*, **38**, 503.

Lazarowitz, R. and Tamir, P. (1994) Research on using laboratory instruction in science. In D.L. Gabel (Ed.) *Handbook of Research on Science Teaching and Learning*. New York, Maxwell Macmillan International.

Lubben, F., Buffler, A., Campbell, B. and Allie, S. (2001) Point and set reasoning in practical science measurement by entering university freshmen. *Science Education*, **85**, 311–27.

Marshall, R. (2002) A practical guide to open-ended coursework investigations. *Physics Education*, **37**, 376–80.

Millar, R. and Driver, R. (1987) Beyond processes. *Studies in Higher Education*, **14**, 33–62.

Reif, F. and St John, M. (1979) Teaching physicists' thinking skills in the laboratories. *American Journal of Physics*, **47**, 950–957.

Roth, W. and Roychoudhury A. (1993) The development of science process skills authentic contexts. *Journal of Research in Science Teaching*, **30**, 127–152.

Salumbides, E. J., Maristela, J., Uy, A. and Karremans, K. (2002) A vision-based motion sensor for undergraduate laboratories. *American Journal of Physics*, **70**, 868–871.

Sharma, M.D., Khachan, J., Chan, B. and O'Byrne J.W. (2005) An investigation of the effectiveness of electronic classroom communication systems in large lecture classes. *Australasian Journal of Educational Technology*, **21**, 137–154.

Sharma, M. D., Mendez, A. and O'Byrne. J.W. (2005) The relationship between attendance in student-centred physics tutorials and performance on university exams. *International Journal of Science Education*, **27**, 1375–1389.

Sharma, M. D., Mills, D., Mendez, A. and Pollard, J. (2005) *Learning Outcomes and Curriculum Development in Physics*. Monash University: Melbourne. Accessed on 30 July 2006 from http://www.physics.usyd.edu.au/super/AUTC/.

Swain, J., Monk, M. and Johnson, S. (1999) A comparative study of attitudes to the aims of practical work in science education in Egypt, Korea and the UK. *International Journal of Science Education*, **21**, 1311–1323.

Thacker, B.A. (2003) Recent advances in classroom physics. *Reports on Progress in Physics*, **66**, 1833–1864.

Trumper, R. (2003) The physics laboratory – A historical overview and future perspectives. *Science & Education*, **12**, 645–670.

Van Hecke, G.R., Karukstis, K.K., Haskell, R.C., McFadden, C.S. and Wettack, F.S. (2002) An integration of chemistry, biology, and physics: The interdisciplinary laboratory. *Journal of Chemical Education*, **79**, 837–844.

Richardson, A., Sharma, M.D. and Khachan, J. (2008) What are students learning in practicals? A cross sectional study in university physics laboratories. *CAL-laborate International*, **16**, 20–27.