Australian Council of Deans of Science

EVIDENCE-BASED PRACTICE IN LEARNING AND TEACHING FOR STEM DISCIPLINES

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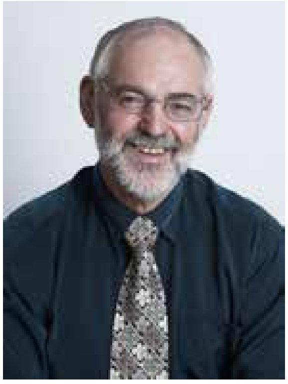
Foreword



The ACDS occasional papers are intended to provide a focus on issues of importance to Australian university science, and to provide authoritative advice. In this paper the ACDS wishes to highlight the conduct of teaching, and encourage teaching staff to be more scientific in their approach.

The stimulus for this paper came from the Office of the Chief Scientist whose Education Adviser, Dr Roslyn Prinsley, referred us to a presentation by Professor Tina Overton, from Monash University. The presentation surveyed evidence-based good practice in teaching. While scientists base their research rigorously on evidence the same cannot be said, broadly speaking, for their teaching. A recent article in *Nature* has called on scientists to reconsider this.

Professor Overton joins with the ACDS Director of its Teaching and Learning Centre, Professor Elizabeth Johnson from Deakin University, to provide in this paper a core of fundamental ideas about teaching and learning practice that have a solid basis in evidence.

John Rice

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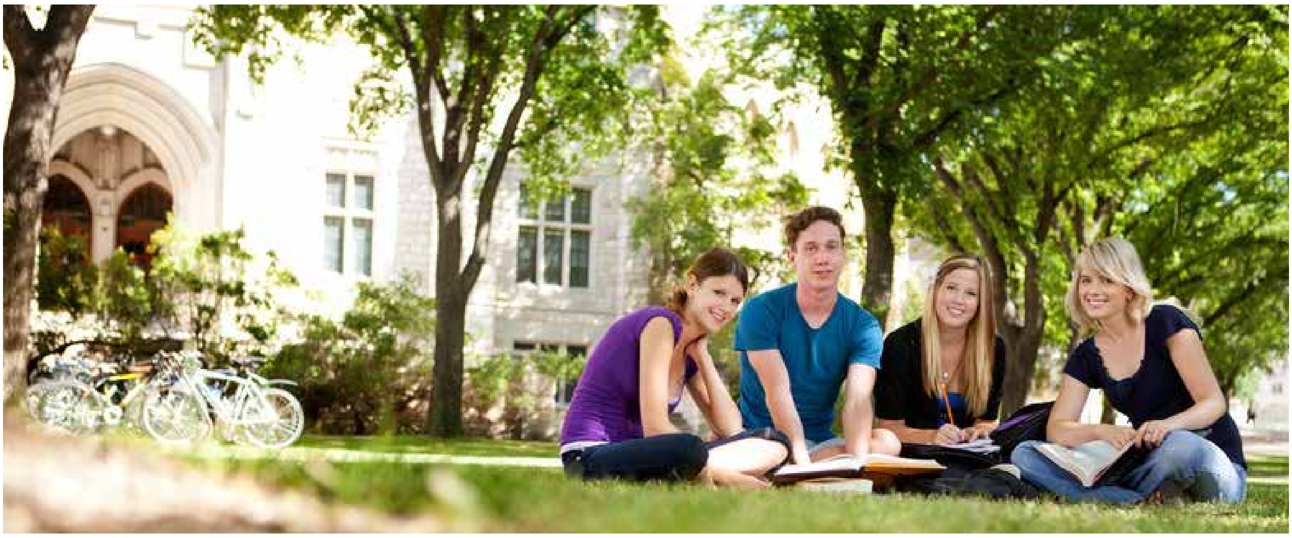
Evidence-based practice in learning and teaching



This paper aims to provide science academics with a quick and easy introduction to some of the big ideas from university level science education research which should have an impact on how we view our teaching. Rallying calls for academics to base their teaching practice based on published evidence have been published repeatedly, most notably in a recent publication in *Nature* (Bradforth et.al., 2015) building on calls from more than a decade ago in *Science* (Handelsman et al., 2004).

In teaching there have been enormous efforts made to improve the quality of learning and the student experience in science disciplines across Australia. However, not all these developments and innovations are based on research evidence; academics may have minimal exposure to education research evidence through no fault of their own, and even the most conscientious may base their practice on anecdotes, instincts or personal prejudices. By contrast, in research, academics consult the published literature in their field, build on the work of others, and take research evidence into account when designing their own research programs. It is a good example of how the multiple roles performed by academics, researcher, administrator and teacher, while they can be intimately related and inform each other, in other ways are often disconnected.

Opportunities to reform learning and teaching arise from the innovation in teaching driven by the pervasive role of technology in the classroom and the shift to mass higher education. Often, local innovation goes unevaluated, or is evaluated in a rather superficial way through the use of 'happy sheets' that record whether students 'liked it'. There is already a large body of published research evidence that measures effects on learning outcomes and this should be informing how the STEM subjects are taught in universities.

Evidence-based understanding of how students learn should underpin effective learning and assessment design. In work commissioned by the US National Academy of Sciences, Kober (2015) proposes that academics should approach teaching in the same way as they approach their research and gives examples of research findings that should inform the design of learning opportunities and assessment tasks. This paper describes some of the most well-established principles derived from learning research that should inform the design of STEM courses. While like all research they remain contestable, they are widely accepted and knowledgeable teachers should know about them.

1. Avoid cognitive overload

The Challenge
Learners have limited capacity to absorb and use new information

The Research

Cognitive load theory has its roots in early cognitive psychology. In 1956 George Miller suggested that humans were able to process seven plus or minus two pieces of information, or 'chunks', in their short-term memory. Australian researcher John Sweller (1988) elaborated on Miller's work to develop ***cognitive load theory*** and described how instructional design can be used to ameliorate the effects of cognitive overload which occurs when the working memory is overloaded. Sweller introduced the concept of '***schemas***' as structures within long-term memory that allow us to treat multiple pieces of information as a single element. Schemas are acquired with experience and undergraduate students may not have acquired the schemas of their teachers. Experience with material leads to changes in the schematic structures of long-term memory and thus enables it to be handled more effectively in the working memory.

Cognitive load has three components (Sweller et. al., 1998). ***Intrinsic load*** is associated with the inherent difficulty of the material being studied. There is little the teacher can do about intrinsic cognitive load but schema can be used to break down or organise the knowledge as learners become more expert. ***Extraneous load*** is associated with the way material is presented to the learner and is in the control of the teacher. For example, teachers can avoid using many words to describe a technical process when a picture would to it more effectively, or avoid introducing irrelevant information into a problem. ***Germane cognitive load*** is associated with the cognitive processes involved in processing information and constructing schemas. Instructors have the opportunity to influence germane cognitive load by encouraging process that help students to construct schemas.

Applying the theory

Careful design of learning experiences can make the most of learning capacity:

- help students to link material into concepts or processes (create schema)
- use visual cues and pictures to simplify the information (reduce extraneous load)
- model and develop expert thinking with lots of practice using application of concepts or linked processes (practice using schema)
- scaffold student learning
- avoid a deluge of facts.

2. Be careful what you measure

The Challenge

Assessing student learning needs to consider inherent limitations of the task

The Research

The practical effects of cognitive load theory in science education have been well reported. In their 1986 paper, Johnstone and El Banna demonstrated how success in problem solving in chemistry and physics undergraduates dropped catastrophically once the number of steps in the problem exceeded seven and the students' working memory became overloaded. Johnstone also demonstrated that students' working memory capacity, which can be readily measured with a simple paper and pen test (Pascual-Leone, 1974), correlated with their scores in solving these problems. So teachers should be clear about what they are measuring; inherent ability or working memory capacity. Providing undergraduates with tasks that exceed their cognitive load dooms them to fail, regardless of their ability.

Applying the theory

Design assessment to:

- measure student learning, that is, what the student knows and is able to do
- align assessment to the learning activities used to prepare for it
- avoid assessment tasks that are strongly time-limited or measure volume of recall (i.e. tasks that measure time-management or cognitive load rather than learning).

3. Ensure students are prepared for laboratory and field

The Challenge

Challenging learning environments, such as laboratories, require a lot of new thinking for students

The Research

Teaching laboratories are environments that place a great demand on students in terms of their working memory and cognitive load. Students are in a new environment, using unfamiliar equipment, following unfamiliar procedures, and are expected to be able to link the activity to material learned in lectures, which may or not be embedded in their long-term memory. The effect of cognitive overload in the undergraduate laboratories has been investigated in two elegant studies, one in chemistry and one in physics (Johnstone et. al.; 1994, 1998).

3. Prepare for laboratory and field Continued

The studies showed that student motivation, performance and retention of knowledge increased if the cognitive load was reduced. This was achieved by making the aims of the activity very clear, making sure that students had received relevant skills training before the activity and, crucially, that they had completed a pre-laboratory activity designed to ensure they knew what they were going to do and why before they entered the laboratory. Johnstone demonstrated stunning improvements in motivation, grades and retention of knowledge. The case for pre-laboratory activities was definitively made over 20 years ago and yet their use is still not widespread across the university sector.

Applying the research

Prepare students to work in challenging environments, such as labs and fieldwork, so they can make best use of the learning experience:

- use pre-lab exercises for preparation
- scaffold learning in the laboratory and the field to build expertise beforehand.

4. Prepare students to learn in lectures

The Challenge

Lectures can introduce lots of bewildering new information that is lost on students

The Research

Cognisance of cognitive load can also help in the lecture environment. Sirhan et.al. in 1999 described a study in which they reduced the number of lectures and replaced them with out of class preparatory reading. This led to improved exam results and a loss of correlation between grades and previous educational background. A similar study was carried out in Australia with bioscience students (Burke da Silver & Hunter, 2009) with remarkably similar outcomes. In this case, the study involved students with and without the prerequisite qualification. Introduction of preparatory reading reduced the failure rate for all students and the difference between the two cohorts was eliminated.

Applying the research

Structure lecture programs to:

- include preparatory exercises that help students to familiarise themselves with language and main concepts
- understand the background of students to assist those with less preparation

5. Embrace flipping

The Challenge
Learners have limited capacity to absorb and use new information

The Research

Studies on the use of the pre-lecture sound very much like the forerunners of the flipped lecture, where students prepare before attending an interactive lecture. The pre-activity in the flipped format can vary and may be in the form of reading or carrying out research but often is in the form of watching a video. The ready availability of technology to capture lectures and produce screencasts has undoubtedly lead to the rise in its popularity. The benefits of the flipped classroom model are not up for debate. Studies such as that recently published by Weaver (2015) demonstrated convincingly that grades improved for students studying via a flipped mode. Notably interactive sessions give students a sound reason to turn up in the face of declining lecture attendance. Of course the value of the flipped model is twofold; the pre-lecture preparation that prepares the student and the switch from a didactic lecture to an active, student-centred face-to-face session.

Applying the research

Flip lectures to make best use of the class time:

- create a learning program that requires and rewards preparation
- create a lecture environment that builds on and applies the preparation.

6. Ensure active learning

The Challenge
Learning requires active engagement

The Research

Active learning has been discussed in the literature for decades; its benefits to learning and motivation are very well documented. The definitive study by Freeman et.al. (2014) was a meta-analysis of 225 studies that reported data on examination scores or failure rates for STEM undergraduates studying through traditional lecturing or active learning. The results showed that average examination scores improved by about 6% when active learning was employed and that students taught by traditional lecturing were 1.5 times more likely to fail than students taught through active learning. Concept inventories are designed to measure deep understanding of foundational principles in a discipline. Active learning had an even greater effect on student performance on concept inventories than the gain seen in more conventional examinations. This implies that active learning is even more important for core disciplinary understanding than for discrete tasks.

6. Ensure active learning Continued

The benefits of active learning are so impressive and so well reported that some have suggested that it is ***immoral*** to continue to teach using traditional didactic lectures (Waldrop, 2015). So the success of the flipped model should be no surprise, combining as it does two approaches that have already been demonstrated to be effective for student learning. Yet across Australian universities, students still sit in lecture theatres, enduring interminable PowerPoint presentations of one-way delivery of information. Is there any wonder students vote with their feet and choose not to attend? Ironically, working through the material for themselves is a more active way of learning than the lecture itself and thus probably more effective for their learning.

Applying the research

Design learning experiences that require the student to actively work with the material:

- ask students to construct their own interpretation of core concepts
- pose problems and challenges that require students to review their own understanding through application
- use peer learning to encourage students to test their understanding and explore different viewpoints
- include multiple modes of learning and assessment that require students to work with material in multiple forms and apply in different ways.

7. Make it authentic

The Challenge

Learner engagement and relevance of the material affects learning outcomes

The Research

Authentic, real life contexts and relevance are known to motivate students (Hmelo-Silver, 2004). Students develop synthesis and judgement skills as they grapple with counter-balancing ideas and facts, and often, an absence of definitive evidence (Lombardi, 2007). The pedagogy that brings together active learning with authentic contexts is problem-based learning (PBL) and related variants. In PBL, students work on real problem scenarios in groups and the tutor takes on the role of facilitator rather than source of knowledge. PBL differs from problem-solving in that students are presented with the problem before they have acquired the relevant knowledge. They define for themselves what they need to know, source information and share it and tackle the problem. PBL is widely used in medicine and other professional disciplines and is making some appearances in STEM education. Variants include structured group learning (Eberlein et al, 2008), and case-based learning (National Centre for Case Study Teaching in Science, 2016). The research shows quite clearly that student learning through PBL have enhanced transferable skills, are better motivated, make better postgraduate students and have better retention of knowledge (Boud & Feletti, 1991).

7. Make it authentic Continued

Problem and inquiry-based pedagogies do have their critics. The 2006 paper by Kirschner, Sweller and Clarke caused quite a stir when it was published as it claims that problem and inquiry-based approaches place too much load on working memory to be effective, leading to cognitive overload. It is important to keep cognitive load in mind when designing learning activities and the inclusion of authentic or real life contexts does increase cognitive load. However, the authors' model of problem and inquiry-based approaches is based on very unstructured activities and, in practice, most models use heavily scaffolded activities, so reducing potential cognitive overload.

Applying the research

Build authentic/real-world applications into learning:

- include problem-based or case-based learning activities
- manage complexity of real-world problems with careful scaffolding of material and/or structured group learning
- check the relevance of problems is clear to your students.

8. Consider the implications of technology

The Challenge

New technologies are changing the way students engage with learning activities and provide opportunities to improve practice

The Research

Technology inevitably influences how we teach in the classroom and beyond, with many teachers assuming that the use of technology always enhances learning. It is common to see lecture theatres of students with laptops open, using them to make notes or annotate slides rather than using paper and pen. Research into the use of technology in the learning environment is running behind its implementation. One interesting study has compared the practice of taking notes on a laptop with taking notes using paper and pen. In 2014, Mueller and Oppenheimer reported that students who took notes in lectures using a laptop did so verbatim, whereas those who made notes using pen and paper made fewer notes, but processed the information and reframed it in their own words, which was beneficial to learning. The students who made paper and pen notes performed better on tests of conceptual understanding thus demonstrating better understanding. Tutors should be aware of such research and share it with their students to ensure that all are aware of the optimal learning environment.

New technologies also introduce the capacity to learn about our students in more rigorous ways. Online learning creates a digital learner footprint that can illustrate how learners use learning resources and interact with universities. This is precious information for teaching teams that can be used to evaluate the efficacy of

8. Consider the implications of technology Continued

materials in real-time and to adjust learning and assessment to better fit the students. It is also proving crucial for universities to better support student's experience of higher education and manage student attrition from courses. Current research investigates how teachers use data from learning and how students can use data to monitor their own learning (Colvin et al, 2015). The field of learning analytics is accelerating as universities move to the minimum of a blend of online and face-to-face teaching and will require teaching teams to develop their own expertise to effectively manage and interpret the large volumes of data.

Applying the research

Consider technology tools in learning design (although more research is needed):

- learning rather than technology should drive innovations
- explore the use of technologies collaboratively with students
- formally evaluate the effect of new technologies on student learning
- use data from learning analytics to inform design delivery and assessment.

Building the evidence

There is a wealth of high quality published research evidence that should be informing how undergraduates are taught in universities. Some of that evidence is already decades old and should be providing academics with the framework within which to structure learning activities. Some of the research is recent and explores the effectiveness of recent advances in pedagogy and technology. A small sample has been discussed in this paper. It is clear that until universities ensure that the education that they provide for undergraduates is rooted in the research evidence then they will continue to fail to produce the graduates that are needed for an effective and vibrant Australian workforce.

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Notes

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