DEMAND EVIDENCE AND THINK CRITICALLY: BUILDING RESEARCH EXCELLENCE IN TOMORROW'S SCIENTISTS

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ABSTRACT
Biomedical science students represent an essential resource for the future scientific workforce. As research scientists are more than their content specialities they must embody core values that govern the development and certification of knowledge. However, the ethos of science is often overlooked in University education in favour of increasing levels of content delivery. This results in graduates with rich content knowledge but limited ability in the generic skills and ethos of a research scientist. To address these concerns, authentic scientific research and communication experiences based on an apprenticeship model were developed to provide realistic insight into scientific ethos and to foster critical thinking, analytical and communication skills. By adapting transitional pedagogy commonly associated with First Year Experience and the Research Skills Development framework, our research-led teaching initiatives allowed students who were considering a career in science true insight into what such a career entails. Students take on the role of 'scientists in training', stepping out of their academic comfort zone within a safe environment where 'perfect' data are no longer generated and adapting to setbacks forms part of the learning process. Success is reflected by positive feedback from students and peers, increased assessment performance, and graduates continuing in science careers.

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RATIONALE
Australia faces a declining scientific workforce. Fewer science students, coupled with an overall decrease in academic performance, threaten Australia's pursuit of an innovative economy. Australia's Chief Scientist challenges us to produce future innovators by nurturing the culture of science in society (Chubb, 2013). Our authentic, research-based, apprenticeship framework directly addresses these challenges by fostering the development of the next generation of research scientists. The cognitive and technical leaps needed for scientific discoveries require more than a deep foundation of knowledge; they require a profound understanding of the ethos of scientific discovery, advanced critical thinking, and superior scientific communication skills. We transition students from highly scaffolded learning experiences towards independent research through the use of the Research Skills Development (RSD) framework (Willison & O'Regan, 2007) and by building discipline specific self-identity. Through these approaches we encourage excellence in the future scientific and medical workforce through the provision of research-ready Biomedical Science graduates.

The RSD framework was developed by Willison and O'Regan (2007) as a conceptual tool for developing student research skills and for providing academics with a structured framework for student progression from structured and guided activities to highly autonomous pursuits (Willison & O'Regan, 2006, 2007; Willison, Pierce & Ricci, 2009). Undergraduate participation in research has many beneficial outcomes including increasing academic performance and motivation to complete studies and improving progression rates into higher degrees by research (Hathaway, Nagda & Gregerman, 2002; Bauer & Bennett, 2003; Willison et al., 2009). As actively engaged scientists, currently investigating heart failure and lung compression, we are committed to integrating research into our undergraduate teaching and are passionate about developing the autonomous research and critical thinking skills of our students. We encourage students to become engaged producers and not just passive consumers of knowledge and foster the students' development of strong professional identities as graduate scientists.

Advanced and Integrated Physiology is a 3rd year undergraduate subject exploring advanced concepts in lung, heart and skeletal muscle function, with adaptations to special circumstances such as exercise as a unifying theme. It has a diverse cohort of up to 40 students from biomedical science, medical laboratory science and science degree programs at James Cook University. Prior to redevelopment in 2009, *Advanced and Integrated Physiology* generated low student satisfaction scores and poor outcomes. We now use an authentic apprenticeship model to build discipline-related self-identity and the RSD framework to produce biomedical research-savvy graduates able to enrich the scientific workforce. Our design adapts the successful transitional pedagogies typically used with First Year Experience programs (Kift & Nelson, 2005) to students on the cusp of graduation. Not only have these strategies led to a dramatic increase in student satisfaction levels and academic outcomes, there is evidence of an increasing number of students continuing to postgraduate qualifications and scientific careers since redevelopment.

MODELLING AND TEACHING KEY CORE SCIENTIFIC VALUES IN A SUPPORTIVE, AUTHENTIC LEARNING ENVIRONMENT

Using a unique combination of the RSD framework and an apprenticeship model, we transition students from the heavily scaffolded learning experiences of earlier years towards becoming apprentice scientists skilled in six core science research values: accuracy, precision, objectivity, testability, scepticism and open communication within three key learning activities: research, critical reflection and communication (Figure 1). The authentic and highly relevant nature of these activities encourages students to take ownership of their learning. We carefully develop autonomy, by progressively decreasing academic control and increasing student input in experimental design, data collection and analysis, manuscript preparation and conference presentations while students gain deep content knowledge. We foster a research scientist identity by modelling the complete research process in a low stakes environment. Personalised experiences of research science arm students with high level transferrable skills which are attractive within a traditional research laboratory and beyond. Building discipline specific student self-identity and embedding the RSD framework into curricula design have been shown previously (Willison, 2012), and in this subject, to increase research skills and encourage more students into research higher degrees. In the words of a 2010 student now undertaking a PhD, ‘The major component of the practical assessment that I feel was of most help, especially when I was an Honours student, was having to write up practical reports as a journal article, complete with a set of instructions for authors. This exercise was really the first taste of real scientific writing that we'd ever had and really helped me when it came to producing my thesis the following year, as I knew exactly what to expect’. Our authentic approach embraces the core tenants of the teaching-research nexus (Willison & O’Regan, 2007), deeply embedding research into classroom teaching, meets James Cook University’s strategic intent of developing research ready graduates and directly addresses Australia’s predicted future deficit in STEM (science, technology, engineering and mathematics) qualified graduates.

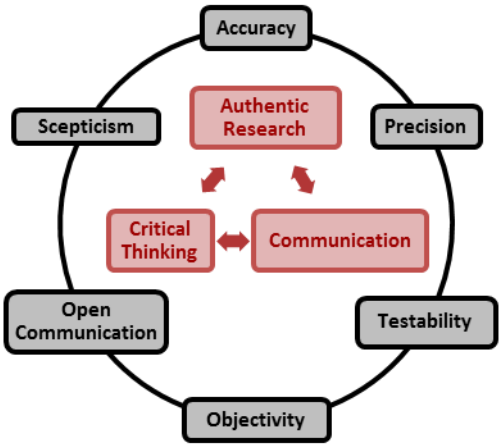

Figure 1: Our apprenticeship model of teaching and learning is scaffolded on 6 key principles (in grey) which underpin science philosophy and research. We embed the teaching and application of all 6 key principles within 3 learning activities (in red); authentic research, critical thinking and communication. These learning activities are designed to be authentic examples of essential skills for a successful graduate scientist.

BUILDING DISCIPLINE-SPECIFIC SELF-IDENTITY

As scientists we are more than the focus of our research or the content that we teach. We embody the core values that govern the development and certification of knowledge. However, the culture of science is often overlooked in favour of delivering content. Redevelopment of *Advanced and Integrated Physiology* was underpinned by the need to both teach and actively model the six core values (Figure 1) in order to foster a 'research scientist' self-identity (self-identity or self-concept being a collection of beliefs that one holds about themselves which includes features such as academic performance, gender, racial identity and the recognition of one's potential and qualities).

Realistic research experiences were integrated into the learning environment (Lombardi, 2007), offering students deep understanding of the culture of their discipline (Callison & Lamb, 2004). This process is similar to an apprenticeship; exposing students to activities they will perform post-graduation (Herrington, Oliver & Reeves, 2003). Students learn not just by listening, but also by doing and mimicking (Lombardi, 2007). For science students, this requires explicit role models and experiences that go beyond skills or knowledge to explore the culture of scientific research. We offer students our personal experiences as scientists and embrace our own unrelentingly high standards to encourage students to develop a strong self-identity of 'research scientist'. High levels of discipline-related self-identity lead to the adoption of deep approaches to learning and increased the students' desire for continued engagement in the discipline (Platow, 2012). As one student commented in 2013, our innovations 'played a direct role in my decision to continue pursuing a career in science'. By overtly representing core values and emphasizing the direct link between core values and scientific success, we seek to produce passionate, engaged graduates who embrace their future science and other careers with integrity and vigour.

The aims of our authentic learning initiatives were to provide students with authentic experiences of scientific research, critical reflection, and communication. We used the key principles of science and scientific research (Figure 1) to underpin the assessments in *Advanced and Integrated Physiology*, ensuring that students were able to act as scientists in training in a low stakes environment where mistakes were part of the learning process. We focused on developing: practical experiences, practical reports, reviewing the literature, and presentation skills into mock scientific pursuits. These activities mimicked scientific research requiring scepticism regarding the accuracy and value of the literature, and communication skills (both written journal articles and conference-style presentations).

> 'This subject opened my eyes to what being a 'research scientist' is really about.'
> (reflection by a 2010 student after completing research honours and 2 years in a science career)

Research means taking risks

De-sanitised authentic research activities immerse students in the 'thrill of the chase', with all the inherent challenges, rewards, and frustrations. Respiratory physiology practicals employ the same techniques used by Dr Munns' in her current research, in which graded exercise tests are used to study the integration of the respiratory system under increasing workloads. Muscle physiology practicals, which investigate the effects of exercise training on skeletal muscle fibres, challenge students to test if their measured changes in exercised vs. sedentary rats match their predictions based on human studies. These authentic research experiences are explicitly designed to be 'real world' scientific research odysseys.

The simplified protocols and perfect data of introductory laboratories have been eliminated. Instead, these experiments are rich with the potential to produce unpredictable results, challenging students in an entirely new way. Students must carefully analyse their data and methodologies and explore published research for explanations of why their results do not match the predicted ideal. Students gain intimate appreciation for core values of accuracy, precision, objectivity and testability by linking the quality of data to their own cognitive and technical skills. By allowing students to take risks, we foster ownership in experimental outcomes, increasing student engagement and inspiring development of high level analytical and technical skills. High levels of engagement are achieved by scholarly dialogue during each practical session, and by requiring students to write research papers for a mock peer-reviewed international scientific journal employing the instructions for authors published by *The American Journal of Physiology*. Students learned that while each peer-reviewed research paper they read was an exemplar of successful scientific communication (in that it had survived the peer-review process and been published), critical analysis invariably revealed a wealth of strengths and weaknesses which could inform students in their own practice as junior scientists. Students valued the teaching approach in sustained ways after engaging in the subject, as reflected in comments such as 'the lecturers gave me a glimpse of the challenges and realities that I now face on a day to day basis, as well as a glimpse of the things that make my career in science so incredibly rewarding' (2013 comment received after the 2010 student completed honours) and 'out of all of the subjects I experienced in my degree this was probably the most practical and realistic introduction into what a career in science really entails' (2013 student presently undertaking Honours in Biomedical Sciences). These authentic research activities build essential skills that underpin not only the most common form of scientific communication but also the most professionally valued.

Critical reflection ensures the integrity of knowledge

Scientists offer more than a toolbox of techniques and a body of knowledge. We make complex decisions about the interpretation of data and critically evaluate published research articles, the mainstay of scientific communication. We believe that rapidly expanding content knowledge necessitates explicit student training in how to identify and evaluate credible sources of information. Critical analysis requires skills drawn from both intellectual training and personal experience. Our students learn from class discussion and personal experience, that knowledge is provisional, and that conflicting interpretations are a valuable resource in the advancement of science. We challenge our students to critique a selection of recent research papers in oral and written formats. We foster a sense of ownership and enable students to explore their own areas of interest by allowing them to create their own shortlist of cutting edge research papers to critique in journal club. Students then improve their critical reflection skills by discussing the research papers, explaining the aims and findings, and placing the results in the context of current research. The teaching staff model the processes of journal article critique for students by leading the first discussions and then allowing students to transition into leading subsequent critiques on newly selected articles. In this way we explicitly train students to critique the work of others as a stepping stone to critically evaluating their own mock research papers prior to submission.

Much to our delight students excelled in this authentic scientific endeavour. Many performed to post-graduate standard, demonstrating superior understanding and innovative thinking in presenting and leading discussions on their chosen papers. Students demonstrated diplomacy and leadership skills when participating in the discussion of a paper being led by a fellow student; if the student leading the discussion was at a loss for words, other students respectfully interjected observations and questions designed to rescue their colleague and promote the critique of the paper being discussed. Due to their superior performances in 2013, 58% of the class earned perfect marks for their engagement. Students expressed pride in how successful they were at a task that they had initially feared. In a 2010 student's words, 'Really like the focus on scientific skills such as journal assessment'.

Communication is the key to knowledge transfer

Research papers and conferences are the mainstay of professional scientific communication. Research papers are an essential currency of academic merit and their crafting is a vital skill for graduates to acquire. We transition students from the heavily guided partial practical reports that are common in 2nd year subjects to writing complete manuscripts suitable for journal submission. This represents a huge advancement in writing quality, data analysis and critically thinking skills. We carefully scaffold this transition by providing well-timed workshops on key skills such as statistics and literature searching and through an open door policy, encouraging students to drop in for support and advice. Conferences are also important forums for exchanging new ideas and encouraging critical debate. We model this experience with a mock conference in which students deliver both oral and poster presentations, forms of communication used in all major international scientific conferences. These authentic activities further develop communication and critical thinking skills. Modelling both the high pressure conference and manuscript writing experiences allows students to build confidence and skills in a low risk environment, where career advancement and professional reputations are not at stake.

SUSTAINED (2009 – 2013) RECOGNITION OF SUCCESS BY STUDENTS AND BOTH JAMES COOK UNIVERSITY AND INTERNATIONAL PEERS

PERFORMANCE INDICATORS

Student feedback by standardised university instruments showed that subject redevelopment improved feedback scores from below school and James Cook University 2008 averages to significantly above in 2009-13. Students were very satisfied with the quality and organisation of the revamped subject (Figure 2), feeling that it inspired them to engage deeply. Feedback scores verify that our authentic learning activities sharpened analytical skills by 36% and increased student motivation (exemplified by a 2014 comment from a 2013 student now taking Honours, 'what we thought seemed like a lot of work at the start of semester proved to be completely worthwhile and also provided the inspiration to continue working in the science field now that we had actually had a taste of what that meant'). The extensive feedback we provided on both written work and during practical activities was very favourably regarded (Figure 2), increasing student feedback scores from 0% (2008) to 87% (2013) agreeing or strongly agreeing. The high standards we set for ourselves and the students engaged them, encouraging them to stretch themselves within a safe environment. In formal institutional feedback students concluded the teaching was 'challenging enough to make us think' (2012) and 'challenging, but plenty of support when needed' (2011).

Student perceptions surveys (2009, 2012 & 2013) showed that 67% of students strongly agreed that 'the journal club sessions, poster session and written reports helped develop their ability to communicate and present research.' Student assessment performance also increased since subject redevelopment; with an 11% increase in high distinction grades (from 6% in 2004-7 to 17% in 2008-13) and 3% increase in distinction grades (from 11% to 14%). Students reflected that the subject was 'challenging' (2011) and 'fascinating' (2012) and 'felt like turning a corner in terms of thinking scientifically' (2010). Students 'really feel as though the publication standard expectations of journal article writes up made me feel more like a real scientist and I learnt a lot and also improved my skills DRAMATICALLY in literature searching skills!' (2010).

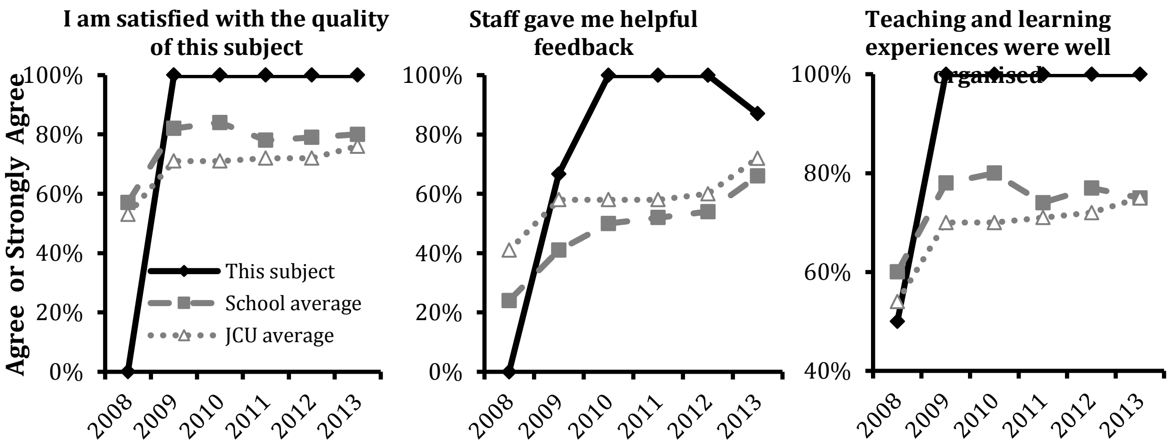

Figure 2: Standardised James Cook University student feedback scores from prior to subject redevelopment (2008) and the 5 years post redevelopment. Subject redevelopment increased student feedback scores from below the school and James Cook University average (2008) to significantly higher (2009-2013). 2013 response rate 35%.

In the 5 years since subject redevelopment, 62% of our graduates immediately continued to postgraduate studies or found employment in a scientific field (compared to approximately 23% in the 6 years prior). These pursuits include honours, masters and PhD programs, research assistants, diagnostic pathology and scientific communication degrees. The increased interest in research has generated the largest enrolment in Honours in Biomedical Sciences in a decade. Our subject is only one aspect of these students' undergraduate journey, however, this high success rate suggests that not only do aspiring scientists elect to enroll in *Advanced and Integrated Physiology*, but that successful completion provides students with the confidence and advanced skills required to pursue their scientific career goals. This is reflected in student comments such as 'I feel as though the subject, and the way it was run by the lecturers was an exceptional preparation for the real world of science' (2010 student with Honours in Biomedical Science in 2011), 'the subject was a fantastic opportunity to really get a taste of what the life of a career scientist is like' (2010 student currently undertaking a PhD) and 'the pracs [*sic*] were interesting and relevant and provided good insight into research' (2013 student anonymous feedback).

SUCCESS CONFIRMED BY INTERNAL AND EXTERNAL PEER REVIEW

International peer review by Dr Robert Carroll, Editor of *Advances in Physiology Education* (the world's leading physiology teaching publication), praised our willingness to offer ourselves as exemplars of science culture and behaviour, and our authentic learning activities, which address a significant weakness in science education 'Science is what scientists do, rather than what they know. Too often, science education emphasizes facts over process. The consequence of this approach is a general public that is incapable of communicating data, following scientific discourse, and unable to employ critical appraisal skills. This course is an excellent model for promoting scientific literacy, an essential step to inform and strengthen the public scientific discourse.'

Mr John Smithson, James Cook University Associate Dean Teaching and Learning (2010-2013), judged that our initiatives were perceived by students as authentic, providing a 'fantastic exemplar of the idea that process, product and student performance were equal in terms of importance.' The subject 'modelled scientific and professional behaviours that will increase the likelihood of students progressing onto research training'. Our innovations were judged by Professor Wayne Hein, Head of the School of Veterinary and Biomedical Sciences, as 'imaginative and pedagogically advanced… [they] promote a culture of inquiry and scholarly dialogue and provides deep insight into the philosophy underpinning scientific research.' Our success with this subject has led us to implement similar innovations in other undergraduate subjects in Biomedical Sciences.

CONCLUSION

A 2006 *Advances in Physiological Education* article urged that 'what is urgently needed is an educational program in which students become interested in actively knowing, rather than passively believing' (Michael, 2006). We have shown that our unique approach of blending the RSD framework with an apprenticeship model of learning, combined with adapting first year experience transitional pedagogies for use with graduating students, achieves this aim. Our innovative approach earned a *Citation for Outstanding Teaching and Learning* at James Cook University in 2013 and received commendation from peers both within James Cook University and from an international expert in science education. We dramatically improved student satisfaction, final assessment success and the number of students progressing to higher degrees in science or advanced scientific posts. The extraordinary success and sustained impact of our teaching approach is best captured in the words of a current postgraduate student: 'it confirmed to me that I wanted to be a research scientist as it was one of the first subjects to really address the critical thinking and writing skills actually required of someone working in the field'. Providing students with authentic scientific experiences, taught by active scientists who use their experiences to enrich the learning environment, arms our graduates with the knowledge, skills and critical thinking needed to facilitate future scientific and medical breakthroughs in Australia.

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