Progressive development of scientific literacy through assessment in inquiry-based biomedical science curricula

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Abstract

A key outcome of science education is the development of graduates' scientific literacy, defined as *"an individual's scientific knowledge, and use of that knowledge to identify questions, to acquire new knowledge, to explain scientific phenomena, and to draw evidence-based conclusions…"* (OECD, 2010; pg 137). These skills are reflected throughout the Science Threshold Learning Outcomes (Jones, Yates and Kelder, 2011). To progressively develop such advanced skills within a broad major like biomedical science, it is essential to guide students along critical learning pathways. We have designed a series of inquiry-based classes to scaffold the development of these skills and vertically-integrated these across the curriculum (Zimbardi, Bugarcic, Colthorpe, Good and Lluka 2013), with this design receiving national recognition as best practice (Elliott, Boin, Irving, Johnson and Galea 2010; Kirkup and Johnson 2013). To facilitate skills development within these classes, students undertake increasingly complex assessment tasks as they progress through each course, requiring them to draw on their developing content knowledge to propose and undertake experiments, and to make conclusions based on their findings and evidence from scientific literature. Longitudinal analysis of a variety of assessment tasks from students across four semesters demonstrates the developmental trajectory of these skills. Specifically, they demonstrate increases in their ability to formulate testable hypotheses with measurable outcomes, their appreciation of cutting-edge methodologies and deeper understanding of the contestable nature of increasingly complex areas of scientific knowledge. This article reports on the design and use of these assessment tasks within the series of inquiry-based curricula, and their impact on the progression of student learning.

Introduction

A key outcome of science education is the development of graduates' scientific literacy, defined as *"an individual's scientific knowledge, and use of that knowledge to identify questions, to acquire new knowledge, to explain scientific phenomena, and to draw evidence-based conclusions…"* (OECD 2010; pg 137). In recent years, there has been considerable interest in the development of students' scientific literacy through undergraduate research experiences (UREs), in which students undertake 'authentic' research experiences. UREs are known to improve student learning across a broad range of scientific skills, including communication, technical, analytic, critical thinking and experimental skills, as well as increasing students' interest in and understanding of careers in science (Lopatto 2007; Thiry, Laursen and Hunter 2011). However, while UREs are clearly beneficial, their expense and associated logistical difficulties mean that their availability is often limited to a small proportion of undergraduate students.

Consequently, curriculum designers have sought to develop alternatives that confer these benefits across a broader proportion of the undergraduate cohort, with inquiry-based activities being seen as a viable alternative. It now is broadly accepted that inquiry-based laboratory classes aid development of many of the skills desirable for science graduates, including critical thinking, communication and research skills (Chaplin 2003; DiPasquale, Mason and Kolkhorst 2003; Willison and O'Regan 2007; Zimbardi et al. 2013). As a result, inquiry-based classes have been designed and implemented across many science disciplines and in cohorts of varying size, providing multiple opportunities for students to progressively develop their scientific literacy across their degree program (Aditomo, Goodyear, Bliuc and Ellis 2011). For many undergraduate science students, particularly those who may not have the opportunity or desire to undertake individualised undergraduate research experiences, these classes may represent the primary vehicle for "the doing of Science" and the development of the inquiry and research skills required to meet the Science Threshold Learning Outcomes (TLOs) (Jones et al. 2011).

To ensure students gain the most benefit from the inquiry-based classes within the science curriculum it is essential to consider a programmatic approach to their design and assessment. However, this is confounded in a generalist degree like the Bachelor of Science (BSc) where students can choose from many courses (subjects) on offer across a variety of majors. Consequently, within a broad major such as biomedical science, it is essential to guide students along 'critical learning pathways' that enable them to progressively develop their scientific skills. We have designed a series of inquiry-based classes to scaffold the development of these skills and vertically-integrated these across the biomedical science curriculum (Zimbardi et al. 2013). To facilitate skills development within these classes, students undertake increasingly complex assessment tasks as they progress through each semester-long course, requiring them to draw on their developing content knowledge to propose and undertake experiments, and to make conclusions based on their findings and evidence from scientific literature. This curriculum design has received national recognition as best practice (Elliott et al. 2010; Kirkup and Johnson 2013).

While laboratory classes have been attributed with the development of many of the scientific skills graduates develop including scientific content knowledge, communication and writing skills, and team work skills (Hodgson, Varsavsky and Matthews 2014), the specific contribution of inquiry-based classes to graduate skills is yet to elucidated. This article reports on the design and use of assessment tasks within a series of inquiry-based curricula in the BSc biomedical science major, and the longitudinal analysis undertaken to assess their impact on the progression of student learning.

Methods

Institutional context

The University of Queensland is a large, research-intensive Australian university, with over 40,000 undergraduate and 8,000 post-graduate students. Over 1,400 students enrol in the undergraduate BSc or BSc dual-degree programs each year, with approximately 500 of these students undertaking a major in Biomedical Science. Within this major, students may choose alternate pathways according to their interest, with course offerings from specific biomedical science disciplines, such as physiology, immunology and infectious diseases, neuroscience, genetics, anatomy, pharmacology and developmental biology. Students in the BSc program may take up to half their courses as electives, choosing courses either within science or from any other program at the university.

Inquiry-based class and assessment task design

Despite this diversity of course offerings, most students within the Biomedical Science major follow common pathways which are comparable to traditional disciplinary majors, with the recommendation of pre-requisite courses promoting this trend. The recognition and utilisation of these pathways allows curriculum designers to develop 'critical learning pathways' in which to promote the progressive development of scientific skills, allowing students to meet the Science TLOs (Jones et al. 2011). One such example of a critical learning pathway is the vertically-integrated, inquiry-based classes in human biology/physiology. This pathway encompasses the first year, second semester course 'Cells to Organisms' (BIOL1040); the second year courses 'Integrative Cell and Tissue Biology' (BIOM2011/2013) and 'Systems Physiology' (BIOM2012) in first and second semester respectively; the third year, first semester course 'Molecular & Cellular Physiology' (BIOM3014) and second semester course 'Integrative Physiology & Pathophysiology' (BIOM3015). While enrolments diminish from approximately 1,000 students in BIOL1040 to 100 in BIOM3015, as students diversify along other pathways, the majority of students who complete this particular pathway will undertake these courses sequentially, if not always in consecutive semesters, with pre-requisite requirements encouraging this progression (Table 1).

Table 1. Structure of 2nd and 3rd year courses within the critical learning pathway in the BSc Biomedical Science major in human biology/physiology

Course code & Name	**BIOM2011 Integrative Cell and Tissue Biology**	**BIOM2012 Systems Physiology**	**BIOM3014 Molecular & Cellular Physiology**	**BIOM3015 Integrative Physiology & Pathophysiology**
Timing	Semester 1, 2nd year	Semester 2, 2nd year	Semester 1, 3rd year	Semester 2, 3rd year
Approximate # of students	500	480	85	95
Prerequisites	BIOL1020 & BIOL1040	BIOM2011 & BIOL2200	BIOM2012	BIOM2012
Lectures/week	3 x 50 min	3 x 50 min	3 x 50 min	3 x 50 min
Practical activities	2 laboratory modules, 3 classes x 3hr each	1 laboratory module, 6 classes x 3hr	1 laboratory module, 3 classes x 3hr / 4 x 2hr workshops	2 laboratory modules, 3 classes x 3hr each
Practical assessment	Experimental plan, proposal and report per module	Draft hypothesis and methods, proposal presentation and report	Laboratory report; 2 meta-learning tasks, 2 oral presentations (workshops)	Pathology worksheet (module 1); Report (module 2)

The development and design of the inquiry-based classes in the first and second year courses BIOL1040, BIOM2011 and BIOM2012, and their associated assessment tasks, has been described in detail previously (Zimbardi et al. 2013). Briefly, the learning pathway commences with short, highly structured, guided-inquiry classes in BIOL1040, which provide strong scaffolding to support early development of students' skills in hypothesis formulation and writing within the scientific genre (Zimbardi et al. 2013), and begins student engagement with scientific literature (Chunduri, Lluka, Kinna, Good, Zimbardi and Colthorpe 2014). As students progress into second year, there is a shift toward more open-ended inquiry. The projects they undertake increase in duration and complexity, with increasing autonomy and student ownership of research questions, and a reduction of scaffolding and academic support (Zimbardi et al. 2013). The associated assessment tasks, while reducing in frequency, also become more complex. There is a shift in emphasis from collaborative hypothesis formulation

and experimental design toward more detailed statistical analyses and interpretation of results, culminating in students being expected to develop novel experiments. These experiments are informed by primary research literature, and the students are required to interpret and integrate their experimental findings with that literature (Zimbardi et al. 2013).

In contrast, the third year classes shift back toward shorter, more structured inquiry-based formats. While the third year students may have less autonomy, the experimental methodologies and analyses they undertake require higher level experimental and interpretive skills, and their findings may be entirely novel. The first semester, third year course BIOM3014 includes two practical components (Table 1). The first of these is laboratory based, consisting of 3 classes each of 3 hours duration taking place in consecutive weeks. Students prepare a culture plate for transfection analysis (Week 1), transfect cells with plasmid DNA carrying reporter genes (Week 2) and analyse the activity of the reporter gene in these manipulated cells and interpret the resulting data (Week 3). The transfection analysis aims to advance understanding of the function of the peroxisome proliferator-activated receptor (PPARγ), a nuclear receptor protein that functions as a transcription factor regulating gene expression, and examines the effect of naturally occurring or artificially introduced mutants of this transcription factor. Assessment tasks associated with this component include an individual 2,500 word laboratory report, with a strong focus on interpretation of their experimental findings in the context of current scientific literature, and a 'meta-learning' task. Meta-learning assessment tasks are short, open-ended questionnaires that prompt students to reflect on their learning and understanding of scientific knowledge (Jackson 2004). In this instance, the meta-learning questions focus on the students' understanding of both the laboratory experiment and appropriateness of its design, and their ability to propose alternative hypotheses and techniques to test those hypotheses, for example students were asked "*Based on the background information and tasks performed in the BIOM3014 practical, what hypothesis would you formulate for this investigation*?" Additionally, students are prompted to consider how well they are able to address these questions and propose strategies they can use to improve their understanding. The second practical component of BIOM3014 is a series of expert and group-based student oral presentation workshops which have been described previously (Colthorpe, Chen and Zimbardi 2014). These workshops provide students with opportunities to build their scientific communication skills, develop their ability to critically evaluate scientific information and their understanding of the contestability of scientific knowledge (Colthorpe et al. 2014).

By the final semester of their degree program, students are expected to have developed high level research skills, including both technical, analytic and communication skills. The final course in this learning pathway (BIOM3015) allows students to hone these skills in two practical modules (Table 1). The first module focusses on pathophysiology. Working in small groups, students characterise a variety of normal and pathological specimens from cardiac, vascular and renal tissue, and tumour specimens from a range of tissues. From these specimens, students develop assessable worksheets consisting of images (sourced online) that illustrate key features of those pathologies, with annotations that both summarise their characteristics and identify key similarities and differences to the specimens they examined. In the second practical module, students use a variety of analytical and molecular techniques to investigate a current area of research. They identify novel genes of interest from microarray databases and investigate these using real time (quantitative/fluorescent) PCR. The assessment for this module is comprised of a short, 4 page individual laboratory report, presenting a justified account of the selection of the genes of interest and methods the student chose, the results from their experiments and an argument for why their gene of interest may be a significant and novel

candidate for future investigations. These classes represent authentic research experiences (Buck, Bretz and Towns 2008), as the students use a rodent model of diabetes to identify new avenues for current research projects underway in the School of Biomedical Sciences, and their reports are forwarded to the research group investigating this model. Finally, BIOM3015 has two meta-learning assessment tasks, similar to those in BIOM3014, which aim to help students identify where they are confident in their knowledge, where gaps in their knowledge, understanding or skills exist, and to reflect on the effectiveness of their study strategies.

The development and design of this curriculum was guided by the principles of the Research Skills Development Framework proposed by Willison and O'Regan (2007), with students undergoing reiterative cycles of inquiry as they progress along this critical learning pathway. The inquiry-based class design moved from structured, guided-inquiry classes in the first year course, through to open-ended inquiry classes with high levels of student autonomy in second year courses, while in the third year classes, students had less autonomy, but the topics addressed in the classes were novel (Buck et al. 2008; Domin 1999; Willison and O'Regan 2007). Throughout the courses, assessment tasks became more complex, with expectations of more advanced scientific writing. Although students receive detailed, individualised feedback on their assessment tasks throughout the courses (details on the type and impact of feedback available in Zimbardi et al. in this special issue), as students progress there is a progressive reduction in the scaffolding provided in the form of prior documentation and academic support.

Analysis of inquiry-based assessment tasks and resources

While the type and weighting of intra-semester assessment tasks varies across each of the 2nd and 3rd year courses, each course includes at least one individual laboratory report. For these reports students are provided with guidelines, describing both the task and expectations associated with its content and structure, as well as criterion-based rubrics, stating the criteria against which the task is marked and the standards associated with each grade band. The resources provided to students in association with the laboratory reports were compared to identify the similarities and differences in their design across the courses. For guidelines, differences in the focus and word length were identified. Within the rubrics, the weighting of task sections (such as introduction, methods, results and discussion) and each criterion were collated, and description of standards for each criterion compared. In addition, the contribution of each laboratory report to the overall course grade was collated.

Analysis of student learning outcomes

The academic records of consenting students in BIOM3015 (n=84; 92% of the cohort) were collated to identify those students who had completed all four courses within the learning pathway in the recommended sequence (n=21, 23% of the cohort). The assessment tasks of a randomly selected sample (n=7) of these students, for whom all individual assessment tasks were available, were analysed in detail to track the development of their scientific writing and research skills. Assessment tasks that were performed by students in groups were excluded from this analysis. The first stage of the analysis was qualitative, focussing on the discussion sections of the laboratory reports: (1) comparing changes in student expression across courses to gauge the development of their understanding of the nature of scientific inquiry and how evidence contributes to knowledge construction; (2) comparing their use of evidence from primary research literature and how they integrated that with their own findings.

As an indicator of how students meet scientific conventions of data presentation, the figure legends created by students within the results section of BIOM3014 and BIOM3015 scientific reports were thematically analysed to identify each element of scientific information present. Elements included the scope of the figure, results description, data presentation, statistical information and experimental information. As similar analyses of figure legends in first and

second year reports have previously been performed (Zimbardi et al. 2013), this analysis completes the longitudinal analysis of their development. The frequency of appearance of each element in each report was compared by ANOVA with Bonferroni's multiple comparisons test using GraphPad Prism 6^{TM} (San Diego, CA, USA), results were considered significant if $p<0.05$.

Average performance on the BIOM3015 end of semester exam of the consenting students (n=84) were compared to the whole cohort (n=91) by ANOVA using GraphPad Prism 6^{TM}. Results showed no significant difference between results (mean +/- SEM) for the consenting students (68.5 +/- 1.73%) and the whole cohort (68.1 +/- 1.71%), suggesting that the consenting students were representative of the entire cohort. This study was approved by the University of Queensland Human Experimentation Ethical Review Committee and all participants provided informed consent.

Results

Assessment task and resource design

Students in the first semester, second year course (BIOM2011) were provided with the most extensive laboratory report guidelines, being 2037 words in length. These provided both detailed instructions pertaining to the expectations on the structure of a scientific report, including the contents of the introduction, methods, results and discussion sections, and on the conventions of the scientific writing genre, with examples of specific aspects such as hypothesis formulation and correct use of abbreviations. The length and detail provided in the guidelines for each course declined thereafter. While those for BIOM2012 and BIOM3014 were similar, being 1580 and 1135 words in length respectively, they provided less detail on general writing style but retained a focus on the structure of scientific reports, with these aspects using 1132 words (72%) and 752 words (66%) of the guidelines for BIOM2012 and BIOM3014 respectively. The BIOM3015 guidelines were the least detailed, being only 726 words long, with a strong focus on the purpose and audience for the report (363 words; 50% of document) and a much shorter description of expected structure (203 words; 28%).

The criteria rubrics also varied across the courses, although those for BIOM2012 and BIOM3014 were essentially identical. While descriptions and weightings of criteria such as language, jargon and grammar were identical across all rubrics, others varied slightly but were in essence the same (Table 2). This was common for criteria pertaining to scientific conventions in style and structure. Greater variation occurred where the focus and emphasis of the task varied, either with a reduction in description length and weighting reflecting a reduction in importance of a particular aspect, or with greater complexity and expectation as students progressed (Table 2). For clarity, descriptions of the highest standard for selected criteria that highlight these differences and similarities are presented (Table 2).

Table 2. Comparison of descriptions of the highest standard for sample criteria and their weightings for scientific reports from across Biomedical Science courses in the 2nd and 3rd year* of the BSc program. Criteria relating to language, grammar and spelling which all have identical descriptors and are worth 10% (BIOM2011 & BIOM3015) or 7% (BIOM2012 & BIOM3014) respectively have been omitted.

Criterion	BIOM2011 Integrative Cell and Tissue Biology: Semester 1, 2nd year	BIOM2012 Systems Physiology and BIOM3014 Molecular & Cellular Physiology : Semester 2, 2nd year & Semester 1, 3rd year	BIOM3015 Integrative Physiology & Pathophysiology: Semester 2, 3rd year
Introduction	Info used to make insightful & convincing argument for hypothesis, which is detailed & complete for specific treatment, measurable outcome & context: 15%	Very well-written, interesting & relevant background info leading to excellent & clearly defined hypothesis & aims: 20%	Makes an insightful & convincing argument for the significance of the line of research & chosen gene of interest: 15%
Methods	All necessary details for subjects included, procedure, treatments & data collection; well designed & controlled: 10%	Methods & data analyses are accurate & concise, & described clearly & completely: 10%	Methods & data analyses are accurate & described clearly & completely: 5%
Results	Text accurately summarises major expt'l findings; Figs / tables complete, skilfully presented; Figure legends/table titles accurate, clear, complete: 15%	Text accurately summarises major findings; High quality data appropriately recorded, analysed & presented: 20%	Accurately summarises major experimental findings, data representation consistent with scientific conventions: 5%
Structure	Info placement creates effective arguments, clearly, cohesively structured throughout, follows scientific genre conventions: 5%	Structure provided is clear & consistent throughout: 3%	Placement of information creates effective arguments that are clearly & cohesively structured throughout: 5%
Discussion: Interpretation	All major findings correctly & insightfully interpreted in terms of underlying physiological mechanisms: 10%	Major findings thoroughly & critically discussed in relation to underlying physiological mechanisms:15%	Writing consistently shows an insightful understanding of the features & mechanisms relevant to the pathology: 20%
Discussion: Knowledge	Writing consistently shows insightful understanding of info relevant to underlying physiological mechanisms and experimental approach: 20%	Consistently clear, concise and logical reasoning throughout: 10%	Major findings were correctly and insightfully interpreted with respect to experimental approach & proposed line of research: 15%
Discussion: Literature	Experimental evidence was thoroughly & critically discussed in relation to scientific literature: 10%	Appropriate literature used throughout to support discussion: 12.5%	Broad, relevant expt'l evidence from scientific literature, synthesised, critically discussed in relation to findings & proposed line of research: 20%
Referencing	Citations AND references are complete, accurate & consistent in style throughout: 5%	Citation style consistent & correct throughout: 2.5%	In text citations AND refs are complete, accurate & consistent in style throughout: 5%

*Criteria and weightings for BIOM2012 in semester 2, 2nd year and BIOM3014 in semester 1, 3rd year are identical.

The change in focus and purpose of the laboratory reports across the courses was also apparent in the changing of weightings of the sections within them. The relative importance of results

and their analysis initially increased in the latter half of second year, before declining in second semester of third year, as the emphasis shifted toward synthesis and evaluation of these results with the research literature (Table 2). There was also an increase in the weighting of the discussion components from 40-45% in the early courses to 60% in the final course as expectations pertaining to interpretation of findings and critical evaluation of evidence from scientific literature increased (Table 2). The amount that each laboratory report contributed to the overall course grade differed somewhat across the courses, with the two reports in BIOM2011 contributing 12% and 16% respectively, and the reports in the remaining courses varying only slightly, with the single reports in BIOM2012, BIOM3014 and BIOM3015 each contributing 20%, 18% and 20% respectively. However, this should be viewed in light of the overall contribution of the laboratory class component in the second year courses, where they contribute 35-40% to the course grade, whereas in third year they contribute only 20-30%.

Table 3. Relative weightings (%) of written scientific report sections collated from rubrics of 2nd and 3rd year courses. Each section of the rubric includes multiple criteria.

	Introduction (%)	Methods (%)	Results (%)	Discussion (%)	Writing & structure (%)
BIOM2011	15	10	15	45	15
BIOM2012	20	10	20	40	10
BIOM3014	20	10	20	40	10
BIOM3015	15	5	5	60	15

Scientific writing

All the students evaluated in detail (n=7) showed progressive development of their scientific writing skills as they progressed through the courses, with their report marks increasing significantly as they progressed from BIOM2011 (62 +/- 3%) to BIOM2012 (85 +/- 1.8%; $p<0.01$), and remaining similar thereafter for BIOM3014 (81 +/- 2.1%) and BIOM3015 (76 +/- 5.6%). Although there was variation in the standard of the work between students, there were a number of common indicators of progress. These included the ways in which they described their evidence, particularly the language regarding its contribution to scientific knowledge. For example, students in early assignments tended to use definitive terminology such as "*The results of this study confirmed the hypothesis...*" (Student 2, BIOM2011 report 1) or "*This study has proven that...*" (Student 5, BIOM2011 report 1) whereas in later reports they were more likely to use more speculative language "*This result suggests that...is most likely*." (Student 2, BIOM3015) or "*...there is no certainty that an association is present, however, the trend observed is of interest*." (Student 5, BIOM3015).

Another key indicator was how they dealt with unexpected or insignificant results and the limitations of their experiments. In early work, students tended to dismiss unexpected or insignificant results as experimental errors, blaming their design, equipment or measurement skills or often small sample size. For example *"As such the lack of effect observed in the current study may be a result of the relatively low intensity and short duration for which subjects exercised.*" (Student 4, BIOM2012). However, these speculations were rarely supported by evidence and may actually have been contrary to the evidence they presented. In the example above, the student presented results that showed consistently large increases in heart rate associated with exercise across subjects, contradicting their suggestion of low intensity exercise as a limitation. In later work unexpected results were more likely to be explained with reference to evidence from the scientific literature, citing alternative theories and using multiple

sources to explain their findings. For example "*No change in the expression of LEP-R in the kidneys of rats exposed to either vehicle or STZ was found (Figure 1)...Alternatively LEP-R is regulated may be hypoleptinemic conditions via changes in the localisation of the receptor. Soluble LEP-R is able to bind circulating leptin and delay degradation (Huang, et al., 2001) as well as inhibit leptin signalling (Schaab, et al., 2012). It is thus possible that in conditions of hypoleptinemia that there may be a proportional decrease in soluble LEP-R without any change in total receptor expression."* (Student 4, BIOM3015). Even commonly cited limitations were more likely to be supported with evidence, for example student 7 stated "*A possible explanation for this lack of definitive response is the number of rat specimens used for the experiment.*" but went on to support this with "*The need to increase the replicates was emphasised by the PCR readout for both STZ rats: 0.850, 0.717 and 0.459, and healthy rats: 0.873, 0.758 and 1.369.*" (Student 7, BIOM3015).

Furthermore, as students progressed, there were changes in the way they integrated evidence of their own findings with the scientific literature. In assessment tasks from early courses, students tended to state their findings and evidence from literature sequentially, with little integration. For example, students often suggested that their findings were either the same as previously published, such as "*No significant increase was found to support the initial hypothesis that the non-dominant hand mean FDS EMG amplitude would be higher than the non-dominant hand during index finger flexion. This is consistent with previous literature concerning both grip strength (Nicolay & Walker, 2005) and action of the first dorsal interosseous (Adam et al., 1998).*" (Student 4, BIOM2011 report 2) or simply differed from published findings, used terms such as 'consistent with', 'supported by', or 'contrary to' previous research without giving sufficient information to determine if their study and those published were comparable or the implications of the similarities or differences. In later courses, students were more likely to integrate their evidence with published literature; using multiple sources of better quality more often, relying exclusively on primary research literature and critically comparing methodologies and results. For example, in the discussion section of their BIOM3014 report the same student commenced a paragraph by stating their finding, referred to their figure and speculated on its implication, then went on to say it "*...is consistent with previous research (Zhang, et al., 2007), implicating both the AF-1 and AF-2 regions in the transcriptional activation of NR4A2. AF-1 is located within the n-terminal domain (Malewicz, et al., 2011) and phosphorylation of S126 (ERK2 and p38) and T132 (ERK2 only) contained in or near AF-1 by ERK2 has previously been directly linked to transcriptional activity of NR4A2 (Jagirdar, et al., 2013; Zhang, et al., 2007)*" concluding the paragraph with further explanatory sentences, and citing three more supporting articles. While there was variation in the extent to which each student demonstrated this skill and at what stage of their progression, all showed improvement across the courses.

Writing of figure legends

The gains in student writing of figure legends within their scientific reports across the first and second year of the learning pathway have been investigated previously, with students in the latter part of second year creating figure legends that are comparable to those produced by professional scientists (Zimbardi et al. 2013). These gains are maintained throughout third year (Figure 1), as students demonstrate that they create figure legends which incorporate elements of scientific information as appropriate for the task. They include elements describing the scope of figure, results and data presentation, and information on the statistical and experimental methods used.

Table 4. Examples of figure legends from laboratory reports (italics) in BIOM3014 and BIOM3015 showing elements of scientific information (element type added in bold)

Student 7, BIOM3014	*Fig. 3: D-H12 deletion results in decrease in cell viability (elaborate) while Deletion of N-Terminal Domain and K91A SUMOylation appears to promote cell survival.* **[Scope of figure]** *Graphs show Mean ±SEM values of % Viability.* **[Data presentation]** *A2058 cells were transfected with NR4A2 isoforms and exposed to increasing doses of H_2O_2.* **[Experimental information]** *Graphs show viability at (A) 100, (B) 200, (C) 300, (D) 400 µM H_2O_2.* **[Results description]** *Data analysed through 2-way ANOVA, Dunnett's post-test (*p<0.05, **p<0.01, ***p<0.001)* **[Statistical information].**
Student 6, BIOM3015	***Figure 1.*** *Real-time PCR analysis of AT2 expression by heart tissue cells* **[Scope of figure]** *of either vehicle treated (Healthy) of STZ treated rats (STZ). Expression levels were averaged from technical replicates (n=3) and normalised against β-actin expression and positive control.* **[Experimental information]** *Values expressed as mean ± SEM.* **[Data presentation]** *ns indicates absence of significance (p>0.05).* **[Statistical information].**

The frequency of use of these elements is comparable to those seen in professional reports (Zimbardi et al. 2013). While students in the first semester, third year were less likely to include information on statistical analyses in their figure legends than in reports for the final course (Figure 1), this was likely to be due to the greater variety of figures presented in the BIOM3014 reports, which included some that were fluorescent microscopy images and therefore did not have associated statistical analyses.

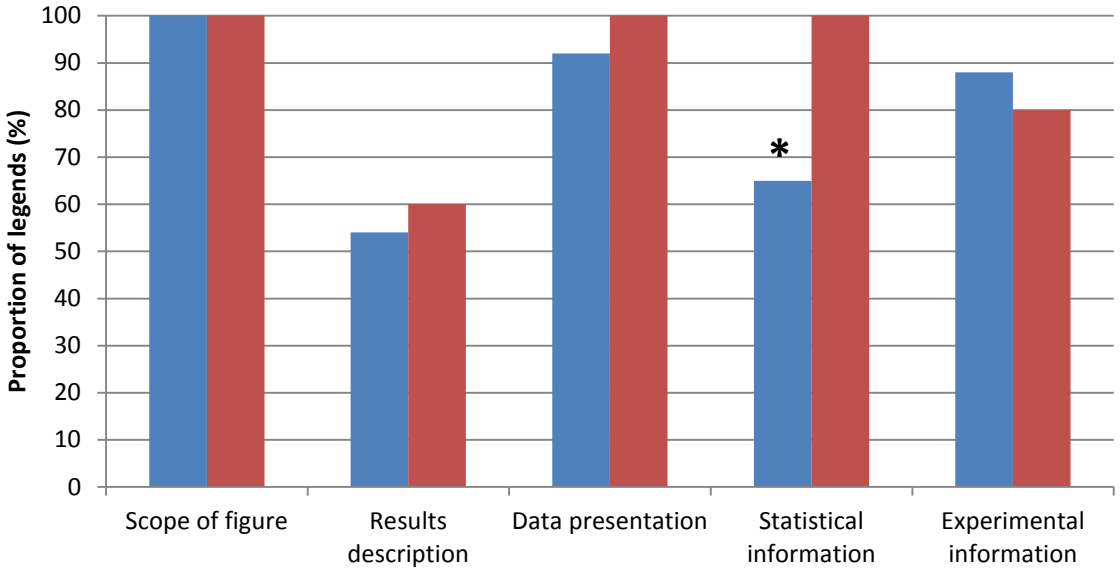

Figure 1. Proportion of figure legends showing elements of scientific information. The figure legends from scientific reports from students (n=7) in BIOM3014 (blue bars; n=26) and BIOM3015 (red bars; n=5) were analysed to identify elements of scientific information. Students included similar information in both reports, with the exception of statistical information, which was significantly less likely to appear in BIOM3014. *, p<0.01 using ANOVA with Bonferroni's multiple comparisons

Discussion

The vertically-integrated series of inquiry-based classes within the BSc Biomedical Science major and BBiomedSc program and their associated assessment tasks were specifically designed to aid the progressive development of students critical thinking, scientific communication and research skills while drawing on and complementing their developing disciplinary knowledge. Each of the assessment tasks had clear task descriptions/guidelines and criteria which were made available to the students prior to commencing the task. The criteria were separated into components that not only represented the structure of a scientific report but also represented different cognitive skills (Table 2), with the introduction and methods criteria representing the lower order cognitive skills of knowledge, comprehension and application, and the results and discussion criteria representing the higher order cognitive skills of analysis, synthesis and evaluation (Bloom and Krathwohl 1984; Crowe, Dirks and Wenderoth 2008). The criteria and descriptions had commonalities between each course, so that the assessment expectations were explained consistently, but were modified so that they build progressively as the students proceed along the learning pathway.

These modifications included the introduction of new elements within criteria, for example the introduction of analysis into the methods and results criteria (Table 2), to expand students' skills in analysis and use of evidence from their own findings, and modifications to the criteria descriptions. For example within the 'Knowledge' criteria the highest standard in the first semester, second year course states that to meet this standard students work must show "...an insightful understanding of relevant underlying physiological mechanisms". In the following two courses this descriptor states that their findings must be "...thoroughly and *critically* discussed in relation to underlying physiological mechanisms". In the final course the descriptor reverts to the earlier language "...an insightful understanding" but of the "...features and mechanisms relevant to the *pathology*" (emphasis added; Table 2). These changes reflect an increase in students' disciplinary knowledge. Initially students are expected to demonstrate their understanding of the normal physiological mechanisms, they then progress toward elucidating mechanisms of more complex physiological processes, to ultimately being able to articulate the physiological mechanisms underlying pathological processes. They also reflect the expectations of increasingly complex cognitive skills as students progress (Bloom and Krathwohl 1984). In addition to these change in descriptions, the relative weighting of individual criteria and report sections also change as students progress (Tables 2 & 3). While many of the criteria changed across courses, there were a small number of criteria, particularly those that focussed on meeting scientific writing conventions (e.g., Table 2 'Structure'), that remained essentially unchanged throughout, reflecting that these genre-specific skills are taught early in the program, and to reinforce the expectation that they should be entrenched in all students scientific writing.

In addition to the changes made in guidelines and rubrics, there was also a reduction in the length and detail of these supporting documents, reflecting the deliberate reduction in scaffolding that takes place as students progress, encouraging students to become more independent learners (McLoughlin 2002). The design and use of scaffolding within the inquiry-based classes was based on Vygotsky's concept of the 'zone of proximal development' which takes into account the cycles of learning maturation that have occurred and are in the process of occurring (Vygotsky 1978). Such that, as students are learning new skills there is strong scaffolding to support their development, once established, the scaffolding reduces as the learners master those skills (Van Der Stuyf 2002). In this vertically-integrated design, as new skills or higher level skills were introduced into the classes or assessment tasks there was additional scaffolding provided, which was then gradually withdrawn. For example, when there

was the increasing focus on statistical analysis in the second semester, 2nd year course, it was supported by a lecture and an analysis tutorial (Zimbardi et al. 2013), where students received guidance from the teaching staff to undertake their analyses. In the first semester, 3rd year course, this was reduced to being just a component in a class discussion, by second semester no general assistance was provided, although students still had the opportunity to seek advice individually.

The examples of student work cited above demonstrate that, as students progressed through the curricula they demonstrated considerable improvement in their scientific writing and showed increasing ability to critically evaluate evidence. Their increasing skills were evident from the earliest reports, with noticeable reductions in the use of inappropriate literature, such as textbooks and review articles, potentially prompted by the marks and feedback they received (see Zimbardi et al. in this issue); marked changes in the language they used to describe findings and their implications, shifting from definitive to speculative terminology, reflecting their developing understanding of the nature of knowledge within science; and increasing integration and critical appraisal of evidence from their own work and that of others. The students also demonstrated that they continued to present their findings in a manner consistent with scientific conventions (Table 4 & Figure 1) and to a similar standard as that of published reports (Zimbardi et al. 2013), despite the progressive decline in weighting of the presentation in the assessment tasks (Table 2). This suggests that once students establish specific skills in scientific writing conventions, they will continue to produce work to a similar standard, even when the skills are not reinforced through supporting documentation. Collectively, these changes demonstrate the maturation in students' inquiry and problem-solving skills, providing evidence of their attainment of the Science TLO 3: Inquiry and problem-solving (Jones et al. 2011).

Together, the design of the inquiry-based classes and their associated assessment tasks, guidelines and rubrics emphasise the increasing importance placed on the higher order cognitive skills, such as analysis of evidence, synthesising of information and evaluation of outcomes (e.g. the 'Literature' criteria, Table 2), and de-emphasising of the lower order cognitive skills, such as application (e.g. the 'Methods' criteria, Table 2) (Bloom and Krathwohl 1984). The impact of this curriculum design on the progressive development of students' critical thinking, scientific communication and research skills is evident in student work, demonstrating the effectiveness of this approach. While the ability of inquiry-based classes alone to contribute to students' understanding of the nature of science may be limited (Schwartz, Lederman and Crawford 2004), the combination of assessment tasks across this 'critical learning pathway', which includes individual and group-based assessment within the inquiry-based classes, critical evaluation of literature in student workshops (Colthorpe et al. 2014), and reflective assessment tasks, collectively contribute to students developing a more mature understanding of the processes, values and underlying assumptions that are intrinsic to scientific endeavour. The findings from this study suggests that, regardless of assessment task genre or format the most important aspect is to ensure tasks are aligned to progressively develop specific skills and reward their attainment.

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