Students' competence and understanding of scientific method in the Life Sciences at the University of KwaZulu-Natal

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GENERAL ABSTRACT

This thesis focuses on describing the conceptions and misconceptions that undergraduate Life Science students hold regarding aspects of the scientific method at the University of KwaZulu-Natal (UKZN). This research is necessary in order that instruction strategies can be formulated and implemented to address these misconceptions, in response to a global call to redefine how science is taught at tertiary level. The University of KwaZulu-Natal is located over a number of campuses with courses and curricula material being taught across campuses by different faculty staff.

The apparent role that faculty staffs' epistemologies, instructional strategies and assessment tools may perform in influencing students' conceptions of scientific method led us to concentrate on some of these areas. Life Science courses are taught by a variety of instructors with differences in their understanding, views and opinions regarding the process of science as well as their pedagogic approaches to teaching this process. We initially investigate the views of lecturers regarding hypotheses and experimental design in their personal research in the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences at UKZN, and how these compare to what is taught at the introductory biology level. Interestingly, only 46.7% of the respondents conduct hypothesis-driven investigations and less than 7% use predictions in their personal research. There is also much variation in faculty members' ideas regarding research hypotheses, alternative hypotheses and their use of sample size, repetition and randomization in their personal research.

Critical analysis of faculty's approach to undergraduate teaching of Life Sciences indicates an over-emphasis of content teaching rather than the development of scientific

reasoning and critical thinking. Undergraduate courses need to engage Life Science students in the process of scientific inquiry where they are encouraged to think deeply about the process of science, and in particular experimental design. Successful Life Science courses train students to critically evaluate experimental design, statistical approaches and inferences in its entirety. Consequently, we tested first and second year Life Science undergraduates understanding of various aspects of experimental design using an open-ended questionnaire. We found that undergraduates performed poorly in 1) producing a completely randomized design of treatments 2) describing the benefits of limiting sources of variability and 3) describing the limitations to the scope of inference for a biologist. They only showed improvement from first to second year in their ability to correctly identify treatments from independent variables. These results add to the growing body of Life Science research that indicates that undergraduate curricula are not adequately producing well-rounded, critical thinking scientists.

Next, we focus on assessments. Faculty staff have been challenged by science educators to change their approach to teaching in order to more accurately reflect the practice of biology. Meeting these challenges requires the critical analysis of current teaching practices and adjustment of courses and curricula through curriculum reform. Assessments play a vital role in providing evidence of effective instruction and learning. Student responses from two formative tests and one final summative examination for an undergraduate biology cohort (n = 416) at UKZN were analyzed both quantitatively and qualitatively to determine students understanding of aspects of the scientific method. Quantitative analyses revealed that the majority of first-year undergraduate students at the end of an introductory biology course were able to identify hypotheses and dependent and independent variables correctly. However, qualitative analyses indicated that sometimes students confuse hypotheses with predictions and are unable to identify independent variables correctly. Critical analyses of the assessments using the Blooming Biology Tool revealed that assessment design can considerably influence student results. It is essential that clear objectives and competencies are set at the outset and that there is a synergistic relationship between instruction and assessment. Assessment design requires careful consideration of content being covered as well as cognitive skills being tested throughout the course.

In addition, we determine the types of conceptions that third year biology students' hold regarding hypotheses, predictions, theories and aspects of experimental design. These conceptions were compared across two geographically separated campuses of the UKZN, namely the Pietermaritzburg (n = 28) and Westville (n = 50) campuses. They were also compared to descriptions located in prescribed textbooks and course manuals throughout their undergraduate biological studies. Results indicate that there is variability between and across campuses in students' descriptions of research hypotheses, predictions and theories, repetition and randomization. These conceptions were sometimes partial conceptions while in other instances they were completely incorrect. Interestingly, many of the students' responses lacked essential elements which could be found in the prescribed textbook and course manuals. The variability in student responses across campuses could be a result of differences in faculty instruction and therefore more research is required to test this. These results also indicate the necessity for courses to be designed with more consistency in concepts to be developed.

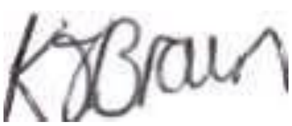
Lastly, we focus on students' competency in aspects of scientific inquiry revealed through a third year research project that is mentored by faculty staff members. This chapter is designed to describe students' ability to effectively apply scientific inquiry at the undergraduate exit year. Biology 390 projects were analyzed from 2012 (n = 26 students), 2013 (n = 46 students) and 2014 (n = 34 students). Journal formatted project write-ups were examined for reference to aims, objectives, hypotheses and predictions. Students' ability to appropriately apply experimental design was also assessed by documenting their use of replicates, sample size, randomization and controls. Conceptions of the broad nature of the scientific process and scientific inquiry were also noted by surveying project introductions, discussions and conclusions for evidence of students' ability to link their research into the greater network of scientific knowledge. There was an overemphasis in the use of statistical hypotheses compared to scientific hypotheses by BIOL 390 students in their project write-ups. Many students used predictions inappropriately and a large majority of students failed to incorporate critical aspects such as randomization and controls into their experimental designs. Explicit didactic discussions by mentors with their students are necessary in order to improve these conceptions of the scientific process. It is suggested that mentors become familiar with both learning theories and common misconceptions associated with the nature of science and scientific inquiry so that they are able to apply these to their mentoring approaches of students conducting research projects.

As a whole, this thesis finds a general lack of understanding of the basic premises of what entails "science" at all levels of undergraduate study within the Life Sciences at UKZN. This worrying trend reflects research from elsewhere, and suggests reform is needed to ensure that UKZN can produce critical higher-order thinking science graduates capable of correctly understanding the full intricacies of the variety of approaches to conducting scientific research. Suggestions for reform include the need for Faculty staff to engage up to date pedagogical research on how science should be taught, a recognition that a move away from knowledge transfer alone towards including skills transfer is needed, training for faculty staff in terms of mentoring skills for participatory research experiences for undergraduates that includes scientific process mentoring, and curriculum reform that recognizes the need to set clear measurable objectives and outcomes for undergraduate courses. Lastly, we also recommend analyzing assessment types used at UKZN in order to ensure that sufficient higher-order cognitive skills are assessed, rather than predominantly lower-order cognitive skills as is currently the case.

PREFACE

The data described in this thesis were collected in Pietermaritzburg, in the Republic of South Africa, from February 2012 to December 2015. Experimental work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Professor Colleen T. Downs.

This thesis, submitted for the degree of Doctor of Philosophy in the College of Agriculture, Engineering, and Science University of KwaZulu-Natal, Pietermaritzburg campus, represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.



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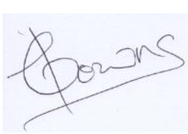
Kelly J. Brown

December 2015

I certify that the above statement is correct and as the candidate's supervisor I have approved this thesis for submission.



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Professor Colleen T. Downs
Supervisor
December 2015

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DECLARATION 1 - PLAGIARISM

I, Kelly Joanne Brown, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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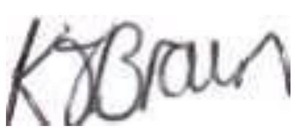

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DECLARATION 2 - PUBLICATIONS

DETAINS OF CONTRIBUTIONS TO PUBLICATIONS THAT form part and/or include research presented in this thesis.

Publication 1

KJ Brown & CT Downs

Whose views to use? Does the scientific approach introduced at first year level correspond with the approach used in research by academics in the biological sciences at the University of KwaZulu-Natal?

Author contributions:

KJB conceived paper with CTD. KJB collected and analyzed data, and wrote the paper. CTD contributed valuable comments to the manuscript.

Publication 2

KJ Brown & CT Downs

Elucidating first and second year misconceptions in experimental design

Author contributions:

KJB conceived paper with CTD. KJB collected and analyzed data, and wrote the paper. CTD contributed valuable comments to the manuscript.

Publication 3

KJ Brown & CT Downs

What are our assessments telling us? Exploring assessments of scientific method questions in a first-year biology cohort

Author contributions:

KJB conceived paper with CTD. KJB collected and analyzed data, and wrote the paper. CTD contributed valuable comments to the manuscript.

Publication 4

KJ Brown & CT Downs

A Case Study Assessing Third Year Biology Students Understanding of Scientific Inquiry Concepts

Author contributions:

KJB conceived paper with CTD. KJB collected and analyzed data, and wrote the paper. CTD contributed valuable comments to the manuscript.

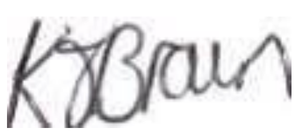
Publication 5

KJ Brown & CT Downs

Assessing conceptual understanding through mentored research experiences in undergraduate students

Author contributions:

KJB conceived paper with CTD. KJB collected and analyzed data, and wrote the paper. CTD contributed valuable comments to the manuscript.



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How are we teaching biology?

Scientists tested a frog
They cut off its legs and shouted "Jump!"
The frog didn't jump.
The scientists concluded that when frogs lose their legs, they become deaf!

"Education is not the learning of facts, but the training of the mind to think" Albert Einstein

Contents

CHAPTER 1

INTRODUCTION

The Scientific Method in the Tertiary Curriculum

The 'Scientific Method' is a term that elicits a variety of reactions from a multitude of individuals. Scientists, philosophers of science, science educators, social scientists as well as the layman all have diverse perceptions of science and its method (Lederman *et al*., 2013). 'Science' originally emerged as a branch of Natural Philosophy and has evolved throughout history and is today associated with a type of knowledge as well as methods from which this knowledge is attained (Kinraide and Denison, 2003). The ultimate aim of science is to collapse the apparent chaos of the universe into concise explanatory models through the appropriate use of its methods (Cohen and Manion, 1980).

Ideas and beliefs concerning science and its methods are largely attributed to an individual's philosophy of science (Cohen and Manion, 1980), whether conscious of it or not. Philosophy has throughout history performed an important role in moulding and changing science. From Aristotle to today there have been twenty-two centuries of scientific investigations guided by philosophy, with only the most recent century displaying a scarcity of philosophical guidance (Gauch, 2003). A review of the past reveals that historical scientists regularly reflected upon the methods they used in their work to the extent that many were also recognized as great philosophers of their time (Gower, 2012). Contemporary scientists on the other hand are quite content to get on with the job of doing science with little thought given to the philosophical basis of their work (Murray, 2001; Wilkins, 2001). This indifference towards philosophy is often reflected in their approach to their work (Murray, 2001).

Today science has grown to encompass a great number and variety of disciplines ranging from the pure sciences, to the biological and social sciences. Each of these disciplines carry a variety of philosophical views and assumptions associated with the methods of science (Abd-El Khalick and Lederman, 2000; Schwartz and Lederman, 2008). Developing curricula at the tertiary level that accurately reflects the complex nature of the real world of science is a difficult task indeed. Consensus over the delineation of the 'scientific method' and its application is complicated and becomes even more problematic when crossing disciplinary borders. Science education is a discipline of science that traverses the boundaries of many scientific disciplines. Challenges therefore arise when teaching and training students in the methods of science. These challenges are particularly evident at the tertiary level, where the majority of faculty members teaching the 'scientific method' are primarily scientists, not trained educators. Scientists largely view the 'scientific method' as something to be applied in their daily research. This contrasts with educationalists who view the 'scientific method' as something to be taught. Effective teaching and training of students in science at the tertiary level requires not only knowledge of science and its methods but also the pedagogical knowledge associated with how students learn (Lederman *et al*., 2014a).

The role of science educationalists is to determine conceptions and misconceptions that have emerged in science and then subsequently to provide solutions for educational reform. Given the complexity of the scientific enterprise it is difficult to know where to begin a search for conceptions and misconceptions in science. Three areas of philosophy seem to have played a role in shaping conceptions: these are ontology, epistemology and logic. A great deal of educational research has focused on these areas, particularly in the area of epistemology. It seems appropriate that an introduction to the scientific method in tertiary education should commence here.

Ontology

Ontology is the area of philosophy that is concerned with the form and nature of reality (Creswell, 2003). It questions the existence of reality, whether it is distinct from the mind or whether it is in fact a construction of the mind (Cohen and Manion, 1980; Morgan, 2007). Ontology also considers how entities relate to each other (Morgan, 2007). Contentious areas of debate in this area of philosophy have focussed on the existence of abstract and unobservable entities as well as the idea of universals, the properties that entities have in common (Cohen and Manion, 1980; Guba and Lincoln, 1994).

Epistemology

The term 'epistemology' comes from the Greek words '*episteme*' meaning 'knowledge' and '*logos*' referring to the 'study of'. Epistemology focuses on the nature of knowledge: its relationship with reality, its validity, its limits and its scope. The study of what makes scientific knowledge distinct from other types of knowledge is known as the epistemology of science (Lederman and Nies, 1997; Musante, 2005). A great many philosophical ideas regarding the epistemology of science have emerged throughout history. Rationalism (the belief that knowledge is gained through reason), empiricism (the belief that knowledge is gained through sense experiences), and constructivism (the belief that all knowledge is a compilation of human-made constructions) have all played a significant part in challenging how scientific knowledge is understood and developed in the many diverse areas of science.

Leaders in science education have recognized that to improve science literacy one requires an understanding of the conceptions and misconceptions that exist in the epistemology of science. A comprehensive review of the literature was undertaken by Lederman (1992) examining over 40 years of research related to the nature of science. From this review he identified specific conceptions of scientific knowledge that are shared across the entire scientific enterprise (Lederman, 1992; Bell *et al*., 2000; Lederman *et al*., 2013). These conceptions have been collectively termed the Nature of Scientific Knowledge (NOS).

The Nature of Science (NOS)

The phrase "Nature of Science" has typically become recognized to refer to the epistemology of science. In essence it refers to the inherent nature and origin of scientific knowledge as well as the characteristics associated with its development (Lederman, 1992; Lederman and Nies, 1997; Abd-El-Khalick *et al*., 1998, Buffler *et al*., 2009; Lederman *et al*., 2014a). Eight aspects of the Nature of Science have been broadly identified and outlined (Lederman, 1992). There seems to be little disagreement among historians, philosophers, and science educators in regard to these eight broad aspects of NOS (Lederman and Nies, 1997).

The conceptions of the Nature of Science are delineated as the following: Scientific knowledge is (1) empirically based; (2) involves imagination and creativity; (3) is tentative; (4) subjective; and (5) influenced by social and cultural factors (Lederman, 1999; Bell *et al*., 2000; Lederman *et al*., 2002; Schwartz and Lederman, 2008). It has also been recognized that scientific knowledge is (6) based both on observations and inferences, which are distinct, and related to these are (7) scientific theories and laws as distinct types of scientific knowledge (Lederman *et* *al.*, 2002; Bayir *et al*., 2013). Last, but not least, is the conception that (8) there is no one single universal scientific method (McComas, 1996; Lederman *et al*., 2002).

(1) Scientific knowledge is empirically based

The empirical-based nature of scientific knowledge is one of the distinguishing traits that characterizes scientific knowledge as scientific (Bednekoff, 2003). The term 'empirical' refers to knowledge that is based on direct and/or indirect observable phenomena (Lederman *et al*., 2002). Science demands the testing of ideas against evidence from the natural world (Akerson *et al*., 2006). In this way human scientific thoughts are brought into correspondence with an external independent reality (Gauch, 2003). Scientific knowledge claims are verified or refuted by empirical facts (Cohen and Manion, 1980; Lederman and Niess, 1997; Murray, 2001), and the reliability and validity of such claims depends on the nature and extent of the evidence supporting them (Pooth, 2002).

(2) Creativity and imagination in the development of scientific knowledge

Science is a creative process (Hutto, 2012). Although it is empirical in nature it also requires creativity and imagination in the development of its knowledge (Lederman *et al.,* 2002; Akerson *et al.,* 2006). Contrary to common belief, it does not involve the unconscious following of a sterile method to generate scientific knowledge (Lederman *et al.*, 2002). A close inspection of scientists' approach to solving scientific problems reveals that they employ a great deal of imagination and creativity in their work, from the generating of questions through to the invention of explanations (Cooper, 2002; Bartos and Lederman, 2014).

(3) The tentative nature of scientific knowledge

Although scientific knowledge is considered reliable and enduring, it can never be considered absolutely certain (Cooper, 2002; Bartos and Lederman, 2014). Contrary to widespread perceptions, scientific knowledge (including facts, theories and laws) cannot be absolutely proven regardless of the extent of accumulating evidence that supports it (Lederman *et al*., 2002; Lederman *et al*., 2014a). All scientific knowledge is provisional and is subject to change when exposed to either new evidence or the reinterpretation of prior evidence (Plotkin, 2003; Akerson *et al*., 2006). New evidence may be made possible through advancements in theoretical ideas and/or the development of innovative and more sophisticated technology (Lederman *et al*., 2002).

(4) The subjective nature of scientific knowledge

Contrary to extensive thought, science is not completely objective (Spiece and Colosi, 2000; Tuyttens *et al*., 2014). While not always intentional, an element of subjectivity does exist in the development of scientific knowledge (McComas, 1996; Lederman and Niess, 1997; Akerson *et al*., 2006). Science never starts with neutral observations but rather depends on a scientist's background and perspective (Charmers, 1982; Spiece and Colosi, 2000). Factors such as prior knowledge, beliefs, goals, training, experiences, expectations, prejudices and the adherence to favored theories not only affect what scientists observe but also the types of questions they ask, the way they investigate and how they interpret their observations (Spiece and Colosi, 2000; Lederman e*t al*., 2002; Bartos and Lederman, 2014; Lederman *et al*., 2014a). Subjectivity may even exist in scientific testing whereby equipment designed to assist in observations may be built or calibrated differently by different scientists (Spiece and Colosi, 2000). Subjectivity may influence observations in field investigations where possible variations may exist in the sites where they are implemented. Occasionally evidence is ignored by scientists, either because it was completely missed or because it was rendered unimportant in accordance with the scientists' prior knowledge (McComas, 1996). Scientific knowledge may be subject to one or a number of these above mentioned factors resulting in an element of subjectivity in its development.

(5) Social and cultural embeddedness of science

Scientific knowledge is also socially constructed and is not, as many believe, simply discovered (Sandoval, 2005). It both affects and is affected by the society and culture in which it is constructed (Abd-El-Khalick *et al*., 2004; Akerson *et al*., 2006; Bartos and Lederman, 2014). Some of the intellectual and social workings that influence both the generation and development of scientific ideas include factors such as financial, political and societal privilege (Goldey *et al*., 2012; Lederman *et al*., 2014a). One of the consequences to scientific knowledge being socially and culturally embedded is the notion that it is not accepted because it is a close approximation of the 'truth' but rather its authority lies in its ability to persuade people of its value (Sandoval, 2005).

(6) Scientific knowledge is based on observations and inferences

Before describing the role of observations and inferences in the development of scientific knowledge it is necessary to distinguish the difference between phenomena and data. Data are characterized by measurements or accounts that may be perceptually attained (Haig, 2005). It is also characteristic of particular contexts and therefore is not as stable and general as phenomena. The role of data is to provide empirical evidence for phenomena. Phenomena on the other hand are abstractions detected through data analysis (Abrahams and Miller, 2008). In other words, they are empirical regularities detected through the analysis of collections of data. Phenomena are considered to be relatively stable, recurrent and general compared to data (Haig, 2005). This stability and repeatability of phenomena is demonstrated through the use of different approaches and different types of data (Alters, 1997; Haig, 2005). Phenomena, not data, are considered as evidence for theories (Akerson *et al*., 2006).

Scientific knowledge is based on observations and on inferences. It is imperative that there is clarity in understanding that these are qualitatively different entities (Bartos and Lederman, 2014). Observations are descriptive statements about phenomena that are 'directly' accessible through experience (Lederman *et al*., 2002). On the other hand, inferences are statements about phenomena that go beyond experience (Holliday and Lederman, 2013). These phenomena are generally unobservable and only identified through their manifestation or effects (Bartos and Lederman, 2014). The relationship between observations and inferences is made clear in the context of their role in scientific knowledge (Akerson *et al*., 2006; Kremer *et al*., 2013).

(7) Theories and laws are distinct types of scientific knowledge

The distinction between scientific theories and laws is closely linked to the distinction between observations and inferences (Lederman *et al*., 2002). There is a pervasive notion, especially within the biological sciences, that theories become laws with an increase in supporting evidence (McComas, 1996). This hierarchical view is inappropriate given that they have different origins and use different kinds of logic in their construction (Murray, 2001). Theories and laws are different kinds of knowledge, the one does not become the other and neither does one have a higher status than the other (Cooper, 2002; Lederman *et al*., 2014a).

Laws are descriptive statements that articulate relationships among observable phenomena (Lederman *et al*., 2014a). While the role of laws is to describe relationships between observable phenomena, the role of theories is to explain and predict facts about phenomena (Karsai and Kampis, 2010). Theories are conjectures of non-observable entities generated through the creative mind and thus only indirect evidence can be used in supporting and establishing their validity (Hodson, 1985; Lederman *et al*., 2002). In order to achieve this, scientists derive specific predictions from theories and test them against data from the real world. An agreement between predictions and empirical evidence lends greater support to and confidence in the theory under examination (Lederman *et al*., 2002). Theories are deemed broader in scope than hypotheses, explaining a large set of seemingly unrelated observations from many fields of investigation (Hodson, 1985; Lederman *et al*., 2002). They are thus considered well-established and highly supported inferred explanations of phenomena.

Theories further play a major role in the generation of new research hypotheses and the guiding of future investigations (Lederman *et al*., 2002). Competing theories are essential in science and it is important to be aware when constructing theories that different explanations can emerge from the same phenomena (Zimmerman, 2000; Gaigher *et al*., 2014).

(8) The myth of a single universal scientific method

This is one of the most widely held misconceptions about science (Lederman *et al.*, 2002). This misconception is regularly exhibited as a belief in a recipe-like stepwise procedure that all scientists follow when they do science (Lederman *et al*., 2002; Marchlewicz and Wink, 2010). Although there are shared activities in science, such as observation, comparison, measuring, testing, speculating, conceptualizing, hypothesizing, analyzing, interpreting, reasoning, justifying and the requirement of empirical evidence in support of scientific explanation, there is no single sequence of prescribed activities that is universally used by scientists in developing reliable scientific knowledge (Lederman *et al.,* 2002; Akerson *et al*., 2006; Bayir *et al*., 2013).

Although the conceptions of the Nature of Scientific Knowledge have been described here as separate entities, it is imperative that there is the understanding that all these scientific knowledge concepts are integrally connected. These conceptions of NOS outlined here are also not definitive but rather those that have been highlighted as being beneficial in distinguishing and understanding what makes science distinct from other knowledge areas (Lederman *et al*., 2014b).

Another epistemological area that has gained much attention in science education research in recent years is the epistemology of Scientific Inquiry (Schwartz and Lederman, 2008; Eastwood *et al*., 2013; Lederman *et al.,* 2013, Bartos and Lederman, 2014; Lederman *et al.*, 2014a). While Nature of Science typically refers to the characteristics of scientific knowledge itself, epistemology of Scientific Inquiry emphasizes what scientists do and how scientific knowledge is generated, justified and accepted (Eastwood *et al*., 2013; Lederman *et al.*, 2014a). Although Nature of Science (NOS) and Scientific Inquiry (SI) are integrally connected in many ways, they are in fact distinct epistemologies and should not be confused (Lederman *et al*., 2014a; Lederman *et al*., 2014b).

Scientific inquiry (SI)

Scientific inquiry is distinct from science processes. Science processes are the activities related to the collection, analysis of data and drawing of conclusions and are often associated with skills such as observing, inferring, classifying, hypothesizing, predicting, measuring, questioning, interpreting and analyzing data (Lederman *et al.,* 2013; Lederman *et al.,* 2014a). These endeavors are often interpreted as scientific inquiry. However, scientific inquiry goes beyond mere process skills, it also includes the epistemological ideas associated with the nature and reasoning behind the process of constructing and justifying scientific knowledge (Schwartz and Lederman, 2008). This higher-order understanding of scientific inquiry is not novel. The

National Research Council (NRC) in 1996 stated in the science education standards that inquiry "requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations" (NRC, 1996, p. 23).

The distinct difference between science processes and scientific inquiry is that the former is related to an ability to perform inquiry whilst the latter entails knowing about the intricacies and critical thinking behind scientific inquiry (Lederman *et al.*, 2014a). This difference in ''doing'' versus ''knowing'' is often missed or conflated by individuals teaching scientific inquiry and these differences result in very different instruction. Whilst one elicits activities associated merely with following scientific recipes and the development of practical skills, the other instills understanding of the rationale behind the investigations being undertaken and the ability to critically analyse and justify the claims associated with the data that has been collected (Lederman *et al.*, 2013).

Science educationalists have outlined conceptions that they believe should develop an informed understanding of Scientific Inquiry (Schwartz and Lederman, 2008; Bartos and Lederman, 2014; Lederman *et al.*, 2014b). These include the conceptions that (1) all scientific investigations begin with a question but do not necessarily test a hypothesis; (2) all scientific inquiry uses evidence to justify knowledge; (3) science uses a variety of investigatory methods (4) these different methods are appropriate to the questions they investigate; (5) all scientists executing the same procedures may acquire different results; (6) inquiry procedures can affect results obtained and scientists are able to recognize anomalous data; (7) there must be coherency between research conclusions and data collected; (8) scientific data and scientific evidence are not analogous; (9) explanations are derived from a combination of empirical data, previous investigations and accepted scientific knowledge and lastly, (10) the products of scientific inquiry is judged through a peer review process within scientific communities (Schwartz and Lederman, 2008; Bartos and Lederman, 2014; Lederman *et al*., 2014b).

Although scientific inquiry is central to multiple disciplines across the natural, physical and social sciences, there is much variation in the degrees to which scientists emphasize different investigatory methods, types of data and previous findings of other researchers in their inquiry (Eastwood *et al*., 2013). Scientific inquiry can be broadly portrayed as descriptive, correlational or experimental (Lederman *et al.,* 2014a). Descriptive research is the type of research that predominates in the early stages of every new science and the purpose of this area of inquiry is to describe (Cohen and Manion, 1980). All basic knowledge science is based upon descriptions and these lay the foundational work necessary for progress in any scientific field (McComas, 1996; Mayr, 1997). Descriptive research is generally guided by "what" questions and therefore although they may make use of statistical hypotheses, scientific hypotheses are not necessary for this type of research. Scientific hypotheses are generally associated with answering "why" questions in science.

In some scientific fields research can progress from descriptive science to correlational and or experimental inquiry. However, it must be noted that not all scientific fields require this progress and descriptive research remains the predominant form of inquiry in many disciplines such as molecular biology, astronomy, and geology (Lederman *et al*., 2014a). Correlational research clarifies relationships among variables highlighted through descriptive research (Romesburg, 1981), whilst experimental inquiry attempts to derive causal relationships through the planned intervention and manipulation of variables (Lederman *et al.,* 2014a). Scientists within these different forms of inquiry also show a variation in the amount of emphasis they place in different types of data such as qualitative or quantitative, historical, or experimental (Eastwood *et al*., 2013).

Epistemology of Science (NOS and SI) and its associated assumptions is essential in defining and understanding scientific knowledge and the processes involved in its development. However, another aspect of philosophy that also performs an indispensable part in the construction of scientific knowledge is logic or scientific reasoning. It is imperative that one has a sound foundation in the logic of science so that one is able to understand how knowledge is constructed, justified and accepted and to be critical participators in the scientific enterprise.

Logic or reasoning

Logic is the area of philosophy concerned with correct reasoning and verification (Gauch, 2003). The reliability of science depends of the appropriate use of reasoning when constructing and evaluating arguments. A comprehensive understanding of the differences between the various types of reasoning as well as where and when they are supposedly applied is necessary to reason effectively in science.

Scientific reasoning or logic reasons between hypotheses and evidence and between premises and conclusions (Fisher, 1995; Gauch, 2003). The main types of reasoning that are used to do this are known as inductive and deductive reasoning. Other types of reasoning suggested in science are abductive reasoning (Haig, 2005) and retroduction (Romesburg 1981; 1989). We shall mainly focus on the differences between inductive and deductive reasoning as these are the predominant types of scientific reasoning used in science. There are three main differences between deduction and induction. The first is a fundamental difference whilst the other two are consequences or elaborations of the first (Gauch, 2003).

The core difference between deductive and inductive reasoning is the difference in the relationship between premises and conclusions. Deduction appears to be preferred by philosophers because a correct premise will automatically guarantee the accuracy of the conclusions given that the truth of an argument is already contained in its premises (Allen, 2001; Kell and Oliver, 2003). On the other hand, in an inductive argument its premises support the truth of its conclusions to a probable degree (Johnson and Onwuegbuzie, 2004). This is because the truth of the conclusion of an inductive argument goes beyond the information in its premises (Gauch, 2003).

The consequence of this difference is the degree of certainty of the argument (Platt, 1964). The certainty of a valid deductive argument is guaranteed given the truth of all its premises and can only be false if one of its premises is false. An inductive argument can never be absolutely certain, but rather at most with a high probability, given the conclusion of the argument containing additional content not given in the premise (McComas, 1996; Gauch, 2003). Thus the uncertainty in an inductive argument is that its conclusion could be false even though its premises are true (Gauch, 2003).

Lastly, is the difference between deductive and inductive reasoning that is most commonly highlighted: the direction of reasoning. Typically, deduction reasons from the general to particular instances, whereas induction reasons from particular cases to general conclusions (Allen, 2001; Reece *et al*., 2011). In scientific reasoning, the ‘generals’ and ‘particulars’ have specific attributes and refer to different areas in deductive and inductive reasoning. The ‘generals’ denote the models or theories which are constructions of a scientist’s mind, whereas the ‘particular instances’ are concerned with the phenomena observed in the physical world (Gauch, 2003).

Deduction is not superior to induction, nor *vice versa*. It is important to understand that they are both necessary in striving for answers to different types of questions and both are indispensable for science (Gauch, 2003, Guthery, 2007). Inductive reasoning is useful for the search of patterns that occur regularly and establishing reliable associations between classes of facts (Romesburg, 1981; Kell and Oliver, 2003). This type of reasoning forms inductive generalizations that are largely descriptive in nature. Although extremely useful in science, these inductive generalizations cannot provide knowledge of mechanisms underlying regular patterns of phenomena (Hutto, 2012).

Understanding the why behind phenomena is the role of deductive logic. It requires the creation of an explanation which is then subjected to verification or falsification through testing. Deductive generalizations are imaginative and commonly refer to unobservables, thus they cannot arise directly from observations through inductive reasoning (Hodson, 1985). Since a process or cause is itself abstract, it can only be tested indirectly by logically deducing one or more test consequences (Romesburg, 1981). The degree to which these consequences align with evidence determines the reliability of the conclusion made through deductive reasoning.

Both deductive and inductive reasoning have and continue to contribute to the development of scientific knowledge (Cohen and Manion, 1980). However, a sound understanding of inductive and deductive reasoning is necessary to discern the appropriate use and position of these types of reasoning in the scientific process as a whole.

Paradigms

An extensive analysis of the history of science conducted by Thomas Kuhn (1970) revealed that scientists work within research traditions he termed ‘paradigms’ (McComas, 1996). A paradigm is: the philosophical intent, motivation and expectation of a researcher with regard to research (Cohen and Manion, 1980; MacKenzie and Knipe, 2006). It is governed by basic beliefs regarding ontology, epistemology and methodology (Guba and Lincoln, 1994). A response to questions regarding these three areas establishes how one aligns to a specific paradigm. As highlighted by Kuhn, paradigms are human-constructs that are provisional and may be challenged when ideas regarding ontology and epistemology are questioned (McKenzie and Snipe, 2006). Alternative paradigms have emerged as a consequence of assumptions associated with certain paradigms being disputed (Guba and Lincoln, 1994).

Today scientists have a range of inquiry approaches to select from and often make choices aligning with paradigms shared by others working in similar fields. Regardless of the name given to it, it is a framework that guides the detection of relevant inquiry questions, the rational use of evidence and the acceptable tests and techniques used in the inquiry process (McComas, 2006). Establishing a theoretical framework is important in providing guidance to all aspects of inquiry (Creswell, 2003). Guba and Lincoln (1994) highlighted that questions related to the purpose or aim of inquiry; assumptions on the nature of knowledge and how it accumulates; the criteria used in judgement of the quality of inquiry and the role of values and ethics in inquiry all assist in determining what paradigm one aligns to.

A variety of research approaches used in the Life Sciences

Classical Biology is a descriptive, inductive type of science but today we are seeing more and more theoretical and mathematically based studies in the Life Sciences (Moore, 2003). Some disciplines in the Life Sciences and other sciences have remained largely descriptive in nature. Descriptive sciences may be better depicted as observational sciences as they rely on observations made either through the naked eye or through simple or sophisticated instrumentation (Mayr, 1997). It is important to note here that knowledge formed through observational science is not inferior to other types of knowledge. Some of the greatest contributions to science are attributed to generalizations based on observations rather than experiments (McComas, 1996; Kell and Oliver, 2003). Equally significant is the fact that theories can change as a result of new observations obtained through inquiry that does not involve experiments (Mayr, 1997). The following section will explore a number of prominent methodologies or approaches utilized by scientists in the Life Sciences. This is by no means exhaustive but rather attempts to emphasize the vast differences that occur in approaches associated with content and context.

The two main approaches emphasized in the Life Sciences are the inductive and hypothetico-deductive approaches. Both are fairly restrictive in their goals and focus on only a part of the inquiry process (Haig, 2005).

Inductive approach

The inductive approach is believed to discover objective accounts of nature through the accumulation of observations and inductive logic (Spiece and Colosi, 2000). It requires the appropriate selection of techniques and the use of rational criteria which has been selected by the scientific community operating within this paradigm (Guba and Lincoln, 1994; Apostolou and Koulaidis, 2010). Progress is believed to occur through the accumulation of new empirical data which is used to either revise or construct new generalizations (Apostolou and Koulaidis, 2010).

Under the inductive scientific approach reliable inductive reasoning is maintained to create and justify theories simultaneously, so that there is no need for subsequent empirical testing (Haig, 2005). In essence this approach assumes the position that empirical generalizations arrived at by inductive reasoning can be promoted to a law if verified (Guba and Lincoln, 1994). This position places enormous faith in the powers of observation and inductive generalization.

Empirical generalizations definitely have a proper niche in the growing edifice of scientific knowledge. However, on its own, the inductive method is unable to discover some kinds of knowledge (Romesburg, 1981). Although it is capable of revealing general correlations, associations and regular phenomenal patterns, it is unable to give explanations or knowledge about the processes that drive these (Hutto, 2012).

Empirical generalizations can play an indispensable part of the scientific process from whence hypotheses or conjectures can emerge (Cohen and Manion, 1980; Romesburg, 1981). The development of theoretical knowledge is another aspect of the inquiry process and this is performed in a number of different ways in the Life Sciences.

The hypothetico-deductive approach

The hypothetico-deductive approach is often heralded as 'The Scientific Method' (Haig, 2005; Karsai and Kampis, 2010). This scientific approach focuses specifically on only one aspect of testing theories: a theory's predictive success (Haig, 2005; Karsai and Kampis, 2010).

A researcher applies the hypothetico-deductive approach by taking an existing hypothesis or theory and testing it indirectly. Both hypotheses and theories are speculative explanations of phenomena and thus require testing to determine their validity and reliability (Romesburg, 1981; Matter and Mannan, 1989). This is achieved through deducing one or more observable predictions which are themselves subject to direct empirical testing (Haig, 2005). Popper (1981) considers the best tests to be those which generate the refutation of or casting doubt over the hypothesis under examination (Matter and Mannan, 1989). The techniques or methodology required in testing theories through the hypothetico-deductive approach generally endeavour to ensure objectivity through the controlling of extraneous variables. Frequentist statistical models are applied to data to determine whether there is a match between the expectations and the data. A correspondence between deduced expectations and observed data is taken as support of the theory (Lawson, 2000; Haig, 2005). Likewise, a lack of correspondence with data counts as a disconfirming incident of a theory (Haig, 2011). Essentially the hypothetico-deductive method exposes alternative theories to facts, and decides on the best theory (Romesburg, 1981). Progress through the use of the hypothetico-deductive approach is associated with the creation of new hypotheses and the competition between rival theories (Apostolou and Koulaidis, 2010).

Although this approach is useful in obtaining reliable knowledge about processes (Romesburg, 1981), there are some criticisms to this approach. Since it concentrates on theory-testing, it intentionally excludes the consideration of the process of discovery in science (Haig, 2005; Blystone and Blodgett, 2006). Being more concerned with theory validation than on the origin or development of theories (Karsai and Kampis, 2010), it assumes that theories arise as mature entities that can be immediately subjected to testing for predictive success. The consequence of this is that most hypotheses and theories tend to be underdeveloped and prematurely submitted to empirical testing (Haig, 1995). Instead of being a secure approach to theory-testing this approach may become nothing more than a 'guess-and-test' approach if not applied appropriately (Chamberlin, 1965; Haig, 1995).

Another criticism is the fact that the hypothetico-deductive approach follows a single-working hypothesis approach. There are two issues related to this particular choice of method. Scientists functioning within a single-working hypothesis approach are susceptible to "the dangers of parental affection for a favourite theory" (Chamberlin, 1965). Fondness and allegiance to a specific theory may direct scientists towards collecting evidence that specifically supports only that particular theory resulting in the inadequate consideration of alternative competing explanations (Elliot and Brook, 2007). As Chamberlin (1965) points out a scientist, even unwittingly, might be "pressing of the theory to make it fit the facts" and the "facts to make them fit the theory", when undertaking a single-working hypothesis approach. Careful consideration must be taken when formulating hypotheses as more than one competing research hypothesis may lead to identical deductions (Guthery *et al*., 2004; Gower, 2012). The second criticism of the hypothetico-deductive approach is that it discourages the synthesis and consideration of multiple effects (Elliot and Brook, 2007). This becomes a problem in a field that has considerable variability, has many interacting variables and where the testing in controlled laboratory environments is not a feasible option.

Multiple working hypotheses

To protect scientists from developing a fixation on a favoured research hypothesis, Chamberlin (1965) proposes the testing of multiple hypotheses through his Method of Multiple Working Hypotheses (MMWH). Outside guarding scientists against personal bias, is the benefit that MMWH affords to protecting scientists against accepting partial 'truths' that could result from the hypothetico-deductive approach (Guthery *et al*., 2004). Chamberlin's MMWH recognizes the possibility that more than one hypothesis may be simultaneously true (Elliot and Brook, 2007).

Ecological systems are generally complex, naturally stochastic with many interacting variables and mechanisms which may operate at different temporal and spatial scales, both progressively and concurrently (Anderson, 2002; Elliot and Brook, 2007; Dochtermann and Jenkins, 2011). The Method of Multiple Working Hypotheses is an approach that has been of great value to fields investigating complex systems and has become increasingly popular in ecology, conservation biology, palaeontology, epidemiology, medicine, geology, meteorology, and astronomy (Elliot and Brook, 2007; Dochtermann and Jenkins, 2011). Its value lies in its ability to test theories in fields where it is particularly difficulty or inappropriate to control for extraneous variables (Anderson, 2002; Lederman *et al.*, 2013), or where temporal and spatial variability exists and where causality includes more than one variable.

There are a number of different models that use the approach of MMWH. A commonly used one in ecology is the Bayesian model or Bayesian information criterion (BIC). The Bayesian account of confirmation uses a statistical approach which assigns probabilities to hypotheses or theories by using the Baye's theorem (Haig, 2005). These probabilities include an element of belief in an event or cause and allows for greater flexibility when evaluating data from complex or incomplete data sets compared to the application of frequentist statistical models often associated with the hypothetico-deductive method (Elliot and Brook, 2007). There are many other information criteria (IC) that use the multiple working hypotheses approach such the Akaike's information criterion (AIC) and Takeuchi's information criterion to name a few but discussion on these are beyond the scope of this introduction (Dochtermann and Jenkins, 2011).

The distinct advantage of applying the Bayes' approach is that one effectively removes the reliance on the falsification of competing hypotheses required by the hypothetico-deductive method whilst simultaneously allowing for an element of uncertainty in the modelling process and in the accumulation of knowledge (Elliot and Brook, 2007).

Inference to the best explanation

In the Life Sciences there are fields that are largely historical in nature. These include geology, biogeography, cladistics, and evolution, considered to be one of the main unifying themes of biology (Le Grange, 2008; Buckberry and da Silva, 2012). Many have argued that these are not scientific because they are not empirical. All science is empirical and involves the testing of ideas against evidence, a requirement that makes it scientific (Bednekoff, 2003; Kremer *et al.*, 2013). However, empirical evidence does not equate to experimental evidence. This is a definition that is both restrictive and misleading. Empirical refers to being "based on observation OR experiment" (Bednekoff, 2003). This broader definition highlights that historical sciences are as much scientific as experimental sciences (Mayr, 1997).

Historical sciences work with phenomena that are unique and unrepeatable (Cooper, 2002). As such they rarely rely on the verification of hypotheses through controlled experiments (Bednekoff, 2003; Blystone and Blodgett, 2006). Since it is impossible to "wind back the clock" or to experiment on the systems involved, historical sciences require a different type of approach to inferring mechanisms (Elliot and Brook, 2007). One of these approaches is inference to the best explanation which accepts a theory when it is judged to provide a better explanation of the evidence than its rivals do (Haig, 2005). The key to developing theories in historical sciences is the reliance on analogy and deduction to organize a plausible explanation, without direct empirical evidence and then apply this to a wide range of facts to demonstrate the explanatory power of the theory (Blystone and Blodgett, 2006). Independent lines of evidence all pointing to the same conclusion allows scientists to claim increasing confidence in a conclusion (Cooper, 2002). Theories in these instances are judged on explanatory breadth rather than predictive success mostly associated with the hypothetico-deductive method (Haig, 2005).

Although this section has not provided all the diverse inquiry approaches applied in the discipline of Life Sciences, it has hopefully highlighted that there are many different approaches to theory appraisal. There is no one way to reliable knowledge. Clarity, consistency, parsimony, density, scope, integration, fit to data, explanatory power, predictiveness, heuristic worth, and application have all been considered relevant evaluative criteria in science (Haig, 1995) and careful consideration of these is necessary when choosing and designing investigations in research.

Distortions of the 'Scientific Method'

There is a caution that one must take when discussing the 'scientific method' because of the implications that follow it. What emerged as a means to provide evidence for scientific ideas has now become so distorted that many cringe at the mention of it. Many of the distortions of the 'scientific method' have occurred through a variety of factors. Here we reflect on a few that may influence students' perceptions of the 'scientific method' at tertiary level.

Teaching of the textbook style 'Traditional Scientific Method'

Many of the distorted views of the scientific method can be attributed to the misrepresentation of science and its method (Hodson, 1998). Superficial knowledge of the scientific method which is often portrayed in textbooks and course outlines, is probably the fundamental reason for these widespread distorted views and misunderstandings (Kosso, 2009). Scholars in secondary education are often introduced to the scientific method as a linear process used to "do science" through experimentation (Akerson and Hanuscin, 2007). Undergraduate students generally commence their first year biological courses with an introduction to the scientific method, frequently found in the first chapter of their textbooks (Gibbs and Lawson, 1992; Kinraide and

Denison, 2003; Kosso, 2009, Kishbaugh *et al*., 2012). Thus both secondary and tertiary students often perceive the scientific method as a procedure to follow in a laboratory, isolated from the greater body of biological knowledge and scientific facts that are taught to them.

The ‘scientific method’ typically depicted in textbooks is what is termed the traditional scientific method (McPherson, 2001; Bonner, 2005; Kishbaugh *et al*., 2012). It is often portrayed as a single list of four or five steps, which may vary slightly from text to text (Blystone and Blodgett, 2006). The traditional scientific method predominantly includes 1) observation 2) proposing a hypothesis from observation, 3) designing an investigation to test the hypothesis and 4) draw conclusions (McComas, 1996; Blystone and Blodgett, 2006; Bowen-Stevens *et al*., 2011 Kishbaugh *et al*., 2012). The traditional scientific method is rooted in the late 1960’s and 1970’s, when Dewey’s (1910) summarized analysis of reflective thinking in science was decontextualized, reconstructed and integrated into school science (Rudolf, 2005). This decontextualized, well-articulated step-wise method made it easy to carry out instructional reform (Tang *et al*., 2010). Over time it became common for science educators and curriculum developers to break down the process of science into these steps and design inquiry activities centering on them (Tang *et al.*, 2010). This further led to misunderstandings that the testing of hypotheses required discrete steps whereby consideration of one step in the linear process could only occur once the previous step was complete (Windschitl, 2004).

In many instances the traditional scientific method was translated practically in school contexts into substantial quantities of rigidly prescribed laboratory manipulations. What Dewey intended to be a mental method that improved students training in mental faculties (Rudolf, 2005), over time evolved into a rigid algorithm which students were expected to memorize, recite and follow as a recipe for practically implementing science (Lederman *et al*., 2013; Lederman *et al*., 2014).

The ‘scientific method’ continues to be emphasized this way in many introductions of textbooks and laboratory report guidelines (Wivagg and Allchin, 2002). Some textbooks explicitly express the scientific method as experimental in nature (McComas, 1996; Lederman, 1999b, Musante, 2009). Testing of hypotheses does not solely rely on experimentation (Bednekoff, 2003) as noted above, and this can produce very restricted and distorted views of scientific method (Lederman, 1999b). Other textbooks may not explicitly mention the scientific method requiring experiments, however, the number of exemplars in their text using controlled experiments may impress upon students that experiments are a necessity in ‘doing’ science (Bednekoff, 2003).

The traditional scientific method is still largely entrenched in the school context despite reform documents best efforts to emphasize that it is “far more than simple rigid steps of the scientific method, that it is far more than just ‘doing experiments’, and that it is not confined to laboratories” (pg. 9) (NRC, 1996). However, the simplicity of the traditional scientific method is no doubt very attractive, offering a convenient way in which to instruct students in the classroom setting. Hodson (1990) claims that most children have no expectations of a single universal scientific method when entering formal education but rather it is the teachers who create this expectation through the continued reference to it. Sadly, Tang *et al*. (2010) found that when teachers focused on inquiry as a discrete set of independent steps they missed instances of productive inquiry in their classrooms.

A number of studies have been conducted on preservice and in-service teachers and their concepts of the nature of science (NOS) (Windschitl, 2003; Akerson and Hanuscin, 2007; Capps and Crawford, 2013). Most elementary teachers are not scientists and their lack of experience affects their knowledge, views and attitudes towards science (Akerson & Hanuscin, 2007). It is only when undertaking scientific investigations first-hand that one understands the complexity and epistemological challenges that are involved with such endeavours (Windschitl, 2004). Teachers that have not had to deal with the predicaments, contradictions and uncertainties associated with coordinating theory, questions, analysing of data and concluding of results will often have naïve views of science and in particular the scientific method (Windschitl 2004; Akerson & Hanuscin 2007). As a result, their ideas and views of science and the scientific method are informed by adopted curricula or textbooks rather than through hands-on experience.

Although students understanding regarding science is predominantly influenced by the teachers that taught them during their school careers, there are other contributors to students' misguided understandings of science. Preconceived ideas formed outside the formal school environment may also influence students understanding of the scientific method. Afonso and Gilbert (2009) noted that cultural beliefs also play a significant role in the tenacity with which students hold onto ideas. This is because changing one's cultural beliefs may threaten social relationships and a sense of identify and belonging.

If preconceived ideas or incomplete and misguided understandings of the method of science are not identified and transformed during a student's high school career, then it is likely that students will retain these ideas when entering their tertiary studies. Problems may arise when faculty teaching introductory courses assume that students entering tertiary education come with informed ideas of science and its method. Unfortunately, it has been shown that students hold fervently to naïve views of science and its method, even after being exposed to different approaches to scientific inquiry at the tertiary level (Bell *et al*., 2003).

As a result of the problems associated with the misrepresenting of the traditional scientific method, there has been a considerable downplay of the steps of the scientific method (Hutto, 2012). Hutto (2012) asserts that this de-emphasizing of the scientific method has elicited misconceptions of its own with regard to scientific inquiry. These include the incorrect use of hypotheses and predictions and students as well as science practitioners thinking they are testing hypotheses when they are in fact not (McPherson, 2001; Hutto, 2012). The traditional scientific method is not incorrect if it is interpreted and understood to be an overall method. It should be a method that is portrayed as a "general pattern of the types of mental activities that occur in the master method, used to obtain, refine and apply knowledge in all fields" (Blystone and Blodgett, 2006; Hutto, 2012) and not as a sequence of rigid steps to be implemented in the laboratory. The overarching view of the scientific method incorporates many different approaches or methodologies to testing hypotheses which may vary according to the content and context of the phenomena under investigation. This I believe is how Dewey intended it to be understood prior to its distortion through the education system.

Faculty epistemologies influencing students' conception of the scientific method

Although few faculty members at tertiary institutions would disagree with the complexity of science, agreement of the instruction in the science process is far less straightforward. Instructors of the method of science play a vital role in portraying the intricacies of this process. The types of instructors involved in training students at the tertiary level may take the form of lecturers, tutors and even postgraduate students. Most instructors at tertiary institutions are trained scientists and have at some level been involved in authentic scientific activities. Where faculty often fall short is their lack of pedagogical training and epistemological knowledge of learning theories and instruction in science (Cocking *et al*., 2000).

Science faculty are generally experts in their field, and often are unaware of the theoretical and conceptual frameworks they have developed through experience and which they instinctively apply to their daily research (Feldon *et al*., 2010). They are also often ignorant of the fact that novices lack these schemas and the ability to organize and apply knowledge to new situations (Coil *et al*., 2010). Koedinger and Anderson (1990) have highlighted that this may result in faculty performing subconscious "step-skipping" behaviours in their teaching, leaving students confused or with incomplete conceptions about the process of science. It must also be noted that practicing scientists are also not immune to the distortions of the scientific method and many do not understand all the components of the scientific method (McPherson, 2001; Hutto, 2012). These distortions may be projected through their instruction, further reinforcing students' misconceptions about the process of science even at the tertiary level.

Science faculty generally work within a specific field of study and develop approaches to science associated with that field (Bonner, 2005). As such different faculty assume different epistemologies regarding science. These epistemologies may differ with regard to the demarcation of knowledge, the status of knowledge, how knowledge changes and ideas regarding the scientific method (Apostolou and Koulaidis, 2010). The epistemologies that faculty hold regarding science and its method have the preponderance of being expressed in the content they teach and in the instructional strategies that they use to teach it. A single philosophical position held by faculty is sometimes reflected in their instruction and choice of curricular activities, whether intentional or not (Apostolou and Koulaidis, 2010).

Laboratory work in tertiary institutions

Traditional tertiary institutions that have large lecture classes often utilize a passive lecture format that is reinforced through standardized laboratory exercises. Large numbers of student enrollment, limited resources and time often lead faculty to providing short manageable practical experiences (Bell *et al*., 2003). These are generally designed as piecemeal activities that are efficient at introducing topics over the course of a semester (Walker and Samson, 2013) but are generally ineffective in achieving meaningful learning in the process of science (Wood, 2009; Spell *et al*., 2014). In other words, doing 'science' does not necessarily mean that students are engaged in scientific inquiry.

These manageable practical experiences have come to be known as traditional "cookbook" laboratory instruction and is often associated with large introductory courses (Wood, 2009). "Cookbook" instruction is typically characterized by laboratory activities that are instructor-defined with prescribed, clear recipe-like methodological directions laid out in laboratory manuals for students to follow in order to reach predetermined outcomes known to both students and instructors (Wood, 2009; Brownell *et al*., 2012; Auchincloss *et al*., 2014). These practical exercises serve little purpose other than to provide students with some training in laboratory techniques associated with the topics highlighted in lectures (Walker and Sampson, 2013). Learning skills in laboratory techniques are an essential part in the training of successful scientists. However, skills will provide the tools required by technicians, not scientists (Karsai and Kampis, 2010).

The use of "cookbook" exercises can seriously undermine students' ability to conceptualize the process of science. The first contribution to this is the fact that most laboratory work has become synonymous with experimentation (Bell *et al*., 2003). The emphasis on experimental testing reflects a single philosophical approach to science (Apostolou and Koulaidis, 2010). This then further fuels possible misconceptions held by students of a single approach to science, through experiments (McComas, 1996; Lederman, 1999). Of course true experimentation is a powerful tool in science used in acquiring and testing knowledge, but it is not the only route to knowledge (McComas, 1996; Sandoval, 2005). Not all scientific investigations are experimental, some are observational, descriptive or correlational (Capps and Crawford, 2013). A better representation of the process of science might require the inclusion of a variety of methods that highlight the diversity of inquiry in science (Hodson, 1998).

The second contribution to the undermining of the process of science through "cookbook" exercises is the focus on "hands-on activities" at the expense of "minds-on activities" (Abd-El-Khalick *et al*., 2004). "Cookbook" laboratory exercises generally engage students at a minimal intellectual level (Brownell *et al*. 2012). Students often follow instructions blindly when conducting "cookbook" type investigations, with little comprehension of what they are doing and why they are doing it (Lawson, 2010; Kluge 2014). They simply operate without any idea of the larger purpose of what they are doing, how their investigations fit into the bigger theoretical picture or even the significance of their results (Hofstein and Lunetta, 2004; Lawson, 2010; Brownell *et.al*, 2012; Kluge, 2014). The expectation of students to merely follow routine, repetitive, prescribed laboratory recipes laid out in practical manuals often depicts science to students as a boring endeavour rather than something that is relevant, creative and exciting (Adams, 2009; Gottesman and Hoskins, 2013; Spell *et al*., 2014).

A third feature of "cookbook" laboratory activities that may affect students' conceptions of the process of science is that they are often designed to ensure that students get the "right" results and draw the "appropriate" conclusions from their results (Walker and Samson, 2013). It also leaves the impression that scientific investigations always give good results. The attainment of highly predictable, unambiguous results is not a true reflection of authentic scientific activities (Spell *et al*., 2014). Biologists have to deal with varied results all the time (Giese, 2012). Indoctrination of always producing “right or wrong” answers through experiments fails to instil in students the complexities of science and how some answers are sometimes unresolved (Wivagg and Allchin, 2002). When students in these laboratory exercises produce variable results they generally relate this to experimental failure, inconclusive data or human error, rather than prompting them to generate and test alternative explanations (Lawson, 2010; Giese, 2012). Experimental failure is an important part of the scientific process. However, undergraduate students who are indoctrinated through “cookbook” lab exercises that laboratory results are guaranteed, are extremely disappointed when they encounter experimental failure in authentic research experiences (Russel et al., 2015). Students need to learn how to overcome challenges when evidence is complex or unexpected and understand how and when to trust scientific claims (Wivagg and Allchin, 2002; Karsai and Kampis, 2010).

A fourth consequence of these “cookbook” experimental activities is the development of the misconception that experiments are a sure route to knowledge (McComas, 1996). This myth is spread through the fact that most of the experimental investigations undertaken in laboratories are conducted as isolated entities which generally culminate in a conclusion of the results. This generates a false confidence that the experimental results are true and fixed. Science does not happen in isolated investigations that end once an experiment has been completed (Gauch, 2003). A single experiment is not sufficient in establishing its conclusions as a part of the body of scientific knowledge (Hodson, 1985). “Cookbook” investigations generally omit the requirement for experimental testing to be subjected to criticism by the scientific community before it can be validated and publicized as part of the body of scientific knowledge (Hodson, 1985, Kell and Oliver, 2003).

Another perception that may arise in students is the view that the laboratory is the only place to do science. Whilst Karsai and Kampis (2010) highlight that the laboratories provide a location in which to test hypotheses through predictions it is not where we do science. Science they proclaim is done in the "investigative mind" and requires the reflective cyclical process of creation, justification and validation of ideas (Spiece and Colosi, 2000; Karsai and Kampis, 2010). The segregation of content teaching in lectures from laboratory exercises further confounds the misconception that science is done in the laboratory. To transform these views might require students partaking in intellectual discussions and arguments and hypothesizing or theorizing in the lecture environment.

Lastly, these "cookbook" exercises seldom provide students with the opportunity to generate hypotheses and predictions or to participate in the designing phase of investigations. While many students have performed experiments and some may have participated in designing experiments, few have an adequate comprehension of the fundamental criteria required to design reliable and valid experiments (Hiebert, 2007; Pollack, 2010). Students who have controlled variables when performing experiments often remain uncertain about designing a controlled experiment and even lack an understanding of how experimental variables affect results (Grunwald & Hartman, 2010). The development of valuable skills such as interpreting how and when to randomize is neglected when students are not provided with opportunities to design investigations.

Training students in the use of statistical models is another area which is lacking in "cookbook" laboratory experiences. A skill in scientific thinking is the evaluation of the strength of evidence in noisy data. Biologists generally deal with variable data and rely on an understanding of statistics (Giese, 2012). "Cookbook" experiences generally focus on generating averages and standard errors or standard deviations. There is also little emphasis on the need to base experimental design on the choice of statistical model. A deep-rooted misconception that many science students have is the erroneous separation of experimental design from statistics (Zolman, 1999). This misconception results in many postgraduates and naïve Life Science researchers undertaking research and often completing data collection prior to considering suitable data analysis procedures (Zolman, 1999). This perpetuates the mistaken understanding that the collection of data is a separate entity to statistical analysis (Hiebert, 2007). This may further develop the incorrect impression that statistical models need only be considered after data collection and that this crucial developmental stage does not play a role in the design of experiments (Zolman, 1999). Such a lack of consideration of statistics in the planning stages of an experiment eliminates a whole dimension of experimental design. The way in which an experiment is set up, repeated, and randomized, is rooted in the statistical model chosen prior to data collection. Such arbitrarily collected data will result in inaccurate and invalid measurements and any inferences based on this data are likely to be the result of chance (Lennon, 2011; Zolman, 1999).

The influence of assessments on measuring students' conceptions in scientific inquiry

There are many challenges to successfully designing and implementing effective inquiry assessments and little is known on instructors' reasoning behind the selection, implementation and interpretation of the assessments they employ to determine students' comprehension of inquiry (Smith *et al.*, 2005; Talanquer, 2013). Some of the factors that can influence the development of assessment tasks include instructors' personal epistemologies about the nature of science (Lederman *et al*., 1998; Lederman *et al*., 2013), their beliefs in the purpose of education, the abilities and motivation of students (Talanquer, 2013), and ease of administration (Pelaez *et al*., 2005).

The way in which assessments are designed however, could undermine the effectiveness of student learning of inquiry and even promote misconceptions that have arisen. If assessments are designed in the absence of clear measurable learning goals, and without close alignment to good instructional practices, then there is the likelihood that the evidences obtained from these assessments will be meaningless in determining the adequacy of students' comprehension of inquiry as well as its capacity to improve future instruction.

Often ineffective assessments mirror the inadequate "cookbook" laboratory that students engage with during 'scientific inquiry' in the laboratory classes. Assessing students in this manner often elicits students' ability to master facts rather than their ability to engage in inquiry through application, evaluation, justification and good reasoning skills (Talanquer, 2013). Poor assessments often assess skills in terms of consecutive steps largely associated with the "traditional scientific method". This further accentuates the myth of the single stepwise scientific method used in inquiry. It has also been found that the cognitive challenge of assessments can strongly influence students' study strategies (Crowe, 2008). A continual emphasis on lower-order cognitive skills will encourage students to focus effort on these skills in assessment preparation. Problems may arise when instructional activities focus on lower-order cognitive skills, but faculty assess higher-order cognitive skills, the result being that students perform badly in assessments because they have not been given enough opportunity to develop deep conceptual understanding (Crowe, 2008).

Different types of assessments can be used depending on the goals of instructors, and different assessments have the potential for measuring different attributes. Consideration is required to ensure that appropriate assessment tools are employed in order to elicit responses from students that can analysed and used to improve student learning and inform teacher instruction. In many tertiary institutions with large class sizes, assessment choices are selected according to ease of administration and do not always have the potential to assess higher-order cognitive skills or elicit students' misconceptions (Pelaez *et al*., 2005). These traditional science assessments often test lower-cognitive skills through multiple-choice or short answer questions (Pellegrino *et al*. 2014). It is necessary for faculty to integrate multiple types of assessment that include both formal and informal as well as qualitative and quantitative assessments in order to track students' learning of scientific inquiry (The American Association for the Advancement of Science [AAAS], 2010).

Students' cultural backgrounds has been shown to also influence the way in which they approach assessments (Arino de la Rubia *et al.* 2014). They hold a variety of views according to their background knowledge, experiences, beliefs and cultural contexts from whence they have come. A lack of consideration of all these aspects in designing assessments may result in students' responses being attributed to factors such as conflict with cultural beliefs and experiences or difficulties with interpretation of the language used in the assessment rather than their comprehension of scientific inquiry.

Curriculum reform

Historically, curriculum development occurred through individual faculty staff's intuition, experience and knowledge of subject content and was taught by faculty staff in a similar manner in which they themselves were taught (Akerson & Hanuscin, 2007, Anderson and Rogan, 2011). Science however is continually evolving. Advancement in technology has resulted in the rate of new information, new discoveries and new insights becoming more prolific than ever before. Universities, colleges and schools are experiencing greater pressure to teach vast volumes of material drawn from an ever expanding and progressively sophisticated body of knowledge (Barnard *et al*., 1993). Undergraduate education faces the challenge of preparing future scientists with the skills needed to cope with this expanse of new information. Coupled with these modern day challenges are the increasing range of misconceptions of the process of science, as discussed above, in both faculty staff and students alike. Curriculum reform needs to address all of these challenges.

A document was produced as a result of a culmination of conversations among biology faculty and students, university administrators and biology professional societies regarding the approaches required to ensure undergraduate biology truly reflects the biology of the 21st century (Woodin *et al*., 2010; Vasaly *et al*., 2014). This document is known as the *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2010) and challenges tertiary institutions to transform their curricula in order to better prepare biology students for a future in the world of science. This document recommends the transformation of content-laden undergraduate biology courses to courses and curricula that focus on core learning goals, core concepts and the development of core competencies (AAAS, 2010).

Transformation requires not only implementing strategies suggested in this reform document but also for faculty to engage with other reform documents as well as current educational and cognitive research literature (Cocking *et al.*, 2000). Developing courses and curricula also requires faculty to cross disciplinary boundaries and cooperate with faculty both within and between courses of different academic levels and disciplines.

Anderson and Rogan (2011) highlight that a curriculum cannot remain constant and must be subject to yearly research, evaluation and development in order to keep up with the rapidly growing developments in biological research. This requires faculty to review and revise a course or curriculum through strategic monitoring of teaching and learning as well as the implementation of new insights published by scientists in the domain of science education (AAAS, 2010). The initial focus in curriculum reform should centre on the learning goals of a course or curriculum, as these not only determine the content and structure of the course, but most importantly the nature in which the course will be taught and assessed (Anderson and Rogan 2011). Wiggins and McTighe (2005) propose a “backward design approach” to course or curriculum development which involves a close connection between assessment, learning outcomes and instruction. Investigations into the effectiveness of the curriculum need to take place in order to determine whether these learning goals are being achieved. The initiation of curriculum reform requires research regarding the underlying problems that exist, followed by the implementation of remedial strategies and the monitoring of their success.

This study focuses on describing the conceptions and misconceptions that undergraduate students hold regarding aspects of the scientific method at the University of KwaZulu-Natal. This research is necessary in order that instruction strategies can be formulated and implemented in order to address these misconceptions. The University of KwaZulu-Natal is located over a number of campuses with courses and curricula material being taught across campuses by different faculty staff.

The apparent role that faculty staffs' epistemologies, instructional strategies and assessment tools may perform in influencing students' conceptions of scientific method led us to concentrate on some of these areas. Firstly, in Chapter 2, we describe faculty's conceptions of hypotheses, replication and randomization and the use of these in their personal research. We then correspond this with what is taught at the first year level in the biological sciences at UKZN. Secondly, in Chapter 3, we focus on experimental design, and first and second year students' ability to identify treatments, randomize effectively and exhibit a cognitive understanding of statistical inference. This chapter also seeks to determine whether students' abilities improve from first year level through to second year level. Thirdly, in Chapter 4, we focus on assessments. The assessments from a first year biology course are analysed to determine the assessment tools used by faculty and the cognitive abilities that each assesses. In Chapter 5, we analyse third year students' concept definitions of principal components associated with scientific inquiry. These include research hypotheses, alternative hypotheses, null hypotheses, predictions, and the role of theory in investigations, as well as repetition and randomization associated with experimental design. These concept definitions are then compared to definitions located in prescribed textbooks and course manuals provided to students during their undergraduate courses. Lastly, Chapter 6, focuses on students' competency in aspects of scientific inquiry revealed through a third year project that is mentored by faculty staff members. This chapter is designed to describe students' ability to effectively apply scientific inquiry at the undergraduate exit year. The conclusion of this study focuses on the areas of concern regarding the specific aspects of scientific method investigated across all five chapters and provides recommendations for curricular reform.

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CHAPTER 2

Whose views to use? Does the scientific approach introduced at first year level correspond with the approach used in research by academics in the biological sciences at the University of KwaZulu-Natal?

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Abstract

The hypothetico-deductive method is still highlighted as a primary model for the Life Sciences in both school curricula and at tertiary level. Much emphasis is given, particularly at the introductory level courses, to hypothesis generation and experimentation. Life Science courses are taught by a variety of instructors with differences in their understanding, views and opinions regarding the process of science as well as their pedagogic approaches to teaching this process. This study investigates the views of lecturers regarding hypotheses and experimental design in their personal research in the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences at the University of KwaZulu-Natal (UKZN) and how these compare to what is taught at the introductory biology level. Interestingly, only 46.7% of the respondents conduct

hypothesis-driven investigations and less than 7% use predictions in their personal research. There is also much variation in faculty members' ideas regarding research hypotheses, alternative hypotheses and their use of sample size, repetition and randomization in their personal research.

Keywords: *Instructor views, introductory biology, hypotheses, experimental design*

Introduction

Science literacy, particularly the understanding of the scientific method, has frequently been a concern for scientists and science educators alike (Afonso & Gilbert, 2009; Akerson & Hanuscin, 2007; McPherson, 2001). A number of factors triggering misunderstandings of the scientific method have been accredited to instructors' personal views, misuse of, portrayal and omission of essential parts of the scientific method (Hutto, 2012; McPherson, 2001).

Pedagogical background of academics

Most tertiary institutions lack formalized curricula to teach undergraduate students (Coil, Wenderoth, Cunningham & Dirks, 2010), and most courses provide just a short description of the syllabus to be covered (Mervis, 2013). This allows for a great deal of freedom to whoever is teaching the course/s. Undergraduate courses are often taught by a variety of instructors from a variety of disciplines. Sometimes these courses are conducted by tutors or graduates with relatively little research experience while others are experts in their field. However, these experts often lack the teaching pedagogies necessary to adequately portray the scientific process they regularly engage with in their personal research. Those that have pedagogical training are often in the minority and may be penalized in traditional research institutions for their emphasis on teaching rather than research output (Mervis, 2013).

Instruction may vary according to the instructor's background (Bonner, 2005). Skills needed to 'think like a scientist' are not always accounted for and different instructors may have different perspectives on how to achieve this. Whilst some may teach process skills in a scaffolded manner, others may assume that students will implicitly acquire the skills somewhere in their four-year degree (Coil et al., 2010).

Disciplinary influences

Faculty not only vary in their approaches to teaching and learning but also hold various personal or experiential beliefs about science and epistemology (Ruhrig & Höttecke, 2013). As a result, faculty members hold different positions in their approach to science. In traditional institutions disciplinary influences often guide the teaching methods of academics (Zimbardi & Myatt, 2012). Researchers undertaking research isolated from other fields over extensive periods of time may consider the cultural approaches of their field to be the norm (Bonner, 2005). A one-dimensional approach familiar to specific academics can result in indoctrination of a single method to doing science and resulting in a greatly impoverished undergraduate curriculum (Apostolou & Koulaidis, 2013, Zimbardi & Myatt, 2012).

Multidisciplinary researchers will perhaps understand the diversity of methods used by the scientific community more. These methods are based on specific epistemological beliefs and assumptions which are approved by the scientific community. Although science does not have one universal method applied to all situations, it does have methods. These methods or approaches are chosen according to particular situations, the nature of a problem or phenomena, and are appropriately selected based on specialized discipline knowledge approved by the scientific community (Hodson, 1998). The selection of these processes, procedures and statistical methods however, will not ensure correct scientific conclusions if not done in light of a well-defined research hypothesis (Zolman, 1999).

Misappropriation of the scientific method by academics

Many scientists and science educators are not immune to misrepresentations of the scientific method and the misuse of this method is becoming increasingly more common in the scientific literature (Hutto, 2012; McPherson, 2001). Of particular concern is the notion of a "hypothesis". The generation and testing of hypotheses is broadly regarded to be the primary means by which experimental science progresses (Allen, 200l; Blystone & Blodgett, 2006; Guthery, Lusk & Peterson, 2004; Kell & Oliver, 2003). However, confusion in the scientific community regarding the terms 'research hypothesis' and 'statistical hypothesis' has led to misappropriation of the scientific process (Hutto, 2012; McPherson, 2001). As a result, statistical hypothesis testing has taken precedence over research hypothesis testing by practicing scientists and students alike (Hutto, 2012).

Research hypotheses are explanations of patterns which identify the mechanism(s) causing the pattern(s) observed (Hutto, 2012; McPherson, 2001). In comparison, the appropriate use of statistical hypothesis testing is to identify or expose non-random patterns, not to explain phenomena (Hutto 2012; McPherson, 2001). Further confusion exists with the use of the term 'alternative hypotheses'. When undertaking statistical hypothesis testing, the alternative hypothesis is generally considered as being the alternative to the null hypothesis (Hutto, 2012). However, alternative hypotheses in terms of research hypothesis testing are researcher generated alternative explanations of an existing pattern (Hutto, 2012). These differences are only understood in light of the role of hypotheses in the testing of theories.

The influence of journal publishing

There are intense pressures in the world of academia to publish vast quantities of original scientific research in order to gain both accreditation and funding for the future (McComas, 1996). One of the strongest facets of the scientific method is the presentation of research to the scrutiny of the scientific community who determines the integrity of the scientific work (Ayers & Ayers, 2007). Peer reviewers in particular disciplines are assigned by journals to 'judge' whether reliable evidence was established through correct methodology and statistical analysis (Walsh, 2014; Wivagg & Allchin, 2002). The irony is that scientific journals require a common standardized style which rarely portrays the actual manner in which research was conducted (Medawar (1990) in McComas, 1996). Limitations of space in journals also results in many essential criteria of studies being omitted (e.g. negative results).

Specific journal requirements for hypothesis-driven research and exclusive views by experts such as "if there is no hypothesis, it is not science" are contributors to researchers inappropriately conducting statistical hypothesis testing under the guise of research hypothesis testing (Kell & Oliver, 2003). The emphasis of this type of isolated fact-finding research has grave consequences. These studies are often incorrectly portrayed as being decisive and universally essential for testing 'hypotheses' (Hodson, 1998). The collection and identification of data is an essential part of the scientific method but it does not constitute the process of science in its entirety (Hutto, 2012; Karsai & Kampis, 2010). Emphasis on statistical testing rather than research hypothesis testing undermines the scientific endeavour. Faculty who focus their research solely on statistical hypothesis testing have limited views of the scientific method. Sadly, many students mentored in this distorted view of the scientific method graduate and begin their publishing career without fully understanding the intricacies involved in understanding natural phenomena, the generation of science knowledge and how science progresses (Kell & Oliver, 2003).

The scientific method in introductory biology courses

A document known as the 'Vision and Change in Undergraduate Biology: A Call to Action' (AAAS, 2010) has recognized that graduates require the development of skills that enable them to cross the disciplinary boundaries of their fields. This is an essential requirement in the world of science of the 21st century. The call to develop multidisciplinary curricula is one that cannot be ignored in traditional research universities. However, there are challenges in implementing this call, particularly among faculty who have diverse views regarding the instruction and epistemology of science.

Introductory biology courses are frequently a prerequisite to many diverse disciplines such as biochemistry, medicine, agricultural economics, biostatistics, microbiology, dietetics, horticulture, environmental sciences, zoology and botany to name a few. Developing an introductory biology course that lays an adequate platform in introducing students to the diverse ways in which Life Scientists perform their work is complicated. Whose perspective should be revealed at the introductory level? How should the scientific method be taught that will give justice to biology as a whole? The first step would be to determine the different understandings and opinions that lecturers possess. It is necessary to look at instructors who teach the introductory course as well as those that teach modules requiring these introductory courses as prerequisites.

University of KwaZulu-Natal

At the University of KwaZulu-Natal, the College of Agriculture, Engineering and Science is subdivided into schools. It includes the School of Agriculture, Earth and Environmental Sciences, the School of Chemistry and Physics, the School of Engineering, the School of Life Sciences and the School of Mathematics, Statistics and Computer Science. The School of Life Sciences focuses on Biochemistry, Biology, Cellular Biology, Ecology, Genetics, Marine Biology and Microbiology. Although the fields of Agriculture, Earth and Environmental Sciences do not fall under the School of Life Sciences, many require the first year level Biology course (BIOL 101) as a prerequisite in their programs.

While the course content of BIOL 101 focuses primarily on the structure and function of living organisms, it does commence with an introduction to the scientific method. The course introduces the scientific method with scientist's two main types of inquiry: discovery science and hypothesis-driven science. However, much of the content taught regarding the scientific method emphasises the hypothetico-deductive approach. Content focuses on defining hypotheses, predictions, treatments, variables, replication and randomization. A brief definition of a theory is provided before continuing with core content such as evolution; biological molecules and processes; DNA replication, transcription and translation; cell theory; prokaryote and eukaryote cells; mitosis and meiosis and introductory genetics. Both the prescribed textbook for this course and the manner in which laboratory teaching is instituted portrays a single universal way of conducting research in the Life Sciences – the hypothetico-deductive approach.

The course is taught across two campuses and by a variety of academic staff. These faculty members conduct research in different disciplines within the Life Sciences and have varied views on how science is conducted. This descriptive study sought to identify faculty's views in the School of Life Sciences and School of Agriculture, Earth and Environmental Sciences on aspects of the hypothetico-deductive approach in relation to the research they conduct and publish in their academic careers. Identification of views and understandings of the scientific process is the first step in determining how introductory biology courses should be taught at the introductory level.

Methods

How do faculty within the College of Agriculture, Engineering and Science interpret hypotheses, alternative hypotheses, repetition and randomization in their discipline of research? Furthermore, how much of these views reflect the content and skills taught at the introductory biology course level? To help answer these questions, a survey was conducted across the Pietermaritzburg and Westville campuses at the University of KwaZulu-Natal (Appendix 1). Ethics clearance for the project was granted by the University of KwaZulu-Natal ethics committee (Protocol reference number: HSS/0814/012D).

This survey consisted of a questionnaire of both closed and open-ended questions covering topics such as discipline, publication experience, hypotheses and experimental design. The first two questions aimed to identify respondents' focus of research and the journal guided requirements for publication in their field. The following four questions consisted of open-ended questions designed to elicit respondent's understanding of research hypotheses, alternate hypotheses, replication and randomization and the use of these in their research.

Hardcopies of the anonymous questionnaire were placed in envelopes with a return address and placed in the mail boxes of academic staff in the School of Agriculture, Earth and

Environmental Sciences and the School of Life Sciences on both the Pietermaritzburg and Westville Campuses.

These particular schools were chosen from the College of Agriculture, Engineering and Sciences as most students graduating in disciplines within these schools require the introductory biology course BIOL 101 as a first-year prerequisite course. A total percentage of programs requiring BIOL 101 as a prerequisite in the College of Agriculture, Engineering and Sciences were calculated. Correspondingly the total number of faculty staff teaching in each of these schools was also determined.

Data coding and analysis

Data from the closed-questions of the questionnaires as well as responses to open-ended questions were transcribed into an Excel spreadsheet. A summary of the respondent's field of research was recorded and percentages of respondents using aim, question, hypothesis and prediction in their publishing career was calculated.

Responses from the open-ended questions on hypotheses, alternative hypotheses, repetition and randomization were read through carefully. Specific codes were identified to describe the different response types that best characterized the answers provided by respondents. It should be noted that responses were not analysed for correctness, only for topics mentioned. The percentage of total codes in each broad category was calculated. Specific responses which highlighted a variety of thoughts regarding hypotheses and experimental design were also selected to aid in discussion.

Results

There were a total of 30 focussed programmes across the schools of Agriculture, Environmental and Earth Sciences and Life Sciences; 87% required BIOL 101 as a prerequisite first year course.

Staff members in the College of Agriculture, Engineering and Science

There was a total number of 289 academic staff in the College of Agriculture, Engineering and Science. The combined total of academic staff in the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences was 154 (54% and 46% respectively). A total of thirty (20% of the 154) faculty staff from these two Schools responded to the questionnaire from both campuses of the University of KwaZulu-Natal (77% Pietermaritzburg, 23% Westville).

Journal publishing requirements of research by academic staff

Overall, only 46.7% of the faculty respondents publish hypothesis-driven research in the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences, and only two staff members mention any use of prediction in their research. Whilst 40% of faculty publish their research in journals only requiring an aim or a question, the results indicated that 13.3% of faculty do not require hypotheses, predictions, questions or aims in publications emanating from their research.

In the School of Agriculture 62.5% of responses (n = 8) referred to the use of aim and or question in their research whilst 37.5% use hypotheses in all or part of their research. Interestingly, in the Earth Sciences (Geology and Geography; n = 4) there appeared to be a polar approach to research where half of the responses indicated no use of aim, question, hypothesis or prediction in their research publications whilst the other half use specifically hypothesis-driven approaches. In the School of Life Sciences (n=18), responses indicated that 50% of individuals use hypotheses in the publication of their research, 39% use aims or questions and 11% do not use any form of aim, question or hypothesis in their publishing. The only academics (n = 2) who claimed to use predictions in their research came from the School of Life Sciences (Fig. 1).

Faculty definitions of a research hypothesis

The majority of the responses defined a research hypothesis as either a statement (33%) or an explanation (20%). The remaining responses characterized a research hypothesis as an idea (13.3%), a research question (6.6%), a null hypothesis (6.6%) and a prediction (6.6%). There appeared to be a lack of clarity amongst faculty as to what exactly these statements were focused on or what the explanations were explaining. Only 46.7% of all the respondents actually described this in their definition of a research hypothesis. Research hypotheses were considered to be explanations or statements about observations (10%), phenomena (10%), relationships (6.6%), data (3.3%), problems (3.3%) and expectations (6.6%). This varied much between individuals.

Only 30% of the definitions on research hypotheses included a description of the purpose of the research hypothesis. These again varied among individuals and include providing solutions to problems (6.6%), testing expectations (6.6%), making predictions (6.6%) and directing investigations, research and experimental design (10%).

Although there was much variation in the defining of a research hypothesis, there appeared to be a general consensus amongst respondents on the conditions of its use. About 73.3% of all respondents stated that research hypotheses must be tested in some way by either being testable (46.6%); verifiable (10%); falsifiable (6.6%) or supported / rejected or proved / disproved (10%).

Faculty understanding of difference between research hypothesis and alternative hypothesis

Analyses of the responses indicated that there are two views held by faculty regarding alternative hypotheses. Those that consider alternative hypotheses to be alternative explanations for the occurrence of a phenomenon (16%) and those that consider the alternative hypothesis to be the opposite, negative or alternative to the null hypothesis (53.3%). Whilst 10% of the respondents regarded research and alternative hypotheses to be the same entity, 10% considered it not applicable or seemed confused by the question (10%).

Faculty use of repetition or sample size in their research

An examination of the responses of the use of repetition and sample size by academics in their research revealed some interesting results. Reference to statistics (statistical significance, power or differences) occurred in 30% of all the responses. Most of these came from the School of Agriculture (5 of the 9). The remaining responses from this school spoke about sample sizes in reference to the population (10-30% of the population).

None of the four responses from the disciplines of Earth and Environmental Sciences clarified repetition or sample size in their research. One of the respondents stated that it depended on the research and that "a small population may not require a large sample size". Within the School of Life Sciences there was a great deal of variation in responses. Four of the five responses from the disciplines of biochemistry, genetics and microbiology stated that there must be between 3-5 repeats. The remainder of the disciplines in the School of Life Sciences referred to either dependence of sample size on statistical probability or variance (46%) whilst others stated a minimum sample size of 3, 5 or 10. One of the respondents from the discipline of ecology stated that they sample “500-600 individuals at 40-60 sites”.

Of the 30 responses only 26.7% gave reasons for their choice of repetitions and sample sizes. These included giving a good representation of population, to identify real differences between experimental groups, to reduce variability and to ensure reliable results. One respondent spoke of “repetitions kept to a minimum to reduce workload” and another referred to using “computer simulations where as a Bayesian statistician he performs millions of replications”.

Faculty consideration of randomization in experimental design of their research

Of the total number of respondents 36.7% do not use randomization in their research. Reasons for this include the use of statistical tools rather than random design in their research or that it is not relevant to the type of investigations that they conduct. The remaining 63.3% of respondents use randomization in their research. Of these 58% stated that they use randomization to reduce or avoid bias and 21% use randomization to reduce the effects of confounding factors. One respondent from the discipline of ecology stated that randomization “gives a general view or representation of the population”. The remaining 16% did not clearly clarify why they use randomization in their research. Thus, the results indicate that within and between the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences there is a great deal of differences in how academics implementing the practical aspect of their research.

Discussion

There were three main features that were highlighted through this study. Firstly, the results indicated that the primary scientific approach (hypothetico-deductive) focused on in the introductory biology course BIOL 101 does not reflect what is used by the majority of faculty within the Schools of Agriculture, Earth and Environmental Sciences and Life Sciences for their personal research. Secondly, respondents' understanding of hypotheses centred around statistical hypothesis testing rather than research hypothesis testing, and thirdly the practical implementation of research varied greatly between different fields and individual faculty across the schools of Agriculture, Earth and Environmental Sciences and Life Sciences.

Research approaches by academics

There appeared to be a disparity between what is taught at the introductory course BIOL 101 and what is practiced by the majority of the academics in their research. More than 40% of the academics in this study published their research in journals that did not require hypotheses or predictions. Even within the School of Life Sciences only half the faculty respondents reported that they publish hypothesis-driven research. This has significance in the training of our students both at the introductory and postgraduate level at the University of KwaZulu-Natal. Generally, graduates who enter postgraduate studies work under the guidance of academics. Graduates are likely to enter their publishing career reflecting the approaches and methods of the academics under whose supervision they have conducted their research.

Academics understanding of hypotheses

The preponderance of journals that do not require hypotheses and predictions has perhaps led to a reduced understanding of the role of hypotheses in science (Anderson, Burnham & Thompson, 2000). The analysis of the open-ended questions of the questionnaire indicated that a large proportion of academics cannot distinguish between research hypothesis testing and statistical hypothesis testing. Only 20% of all respondents recognized a research hypothesis as an explanation, while most fail to clarify that it is an explanation of the mechanisms underlying the patterns of phenomena (Hutto, 2012). The explanations of research hypotheses tend to rather highlight individuals' tendency to concentrate on statistical hypothesis testing rather than research hypothesis testing (Guthery, Lusk & Peterson, 2004) This is further highlighted by more than 80% of the individual respondents considering an alternative hypothesis to be the opposite of or same entity as a null hypothesis. This limited understanding of research hypotheses suggests that the majority of faculty are more likely to undertake predominantly descriptive research determining non-random patterns rather than to conduct research that leads to explanations of phenomena (Hutto, 2012). These particular studies are essential in the scientific process but do not necessarily produce theory-dependent research.

Academics decisions regarding sample size, repetition and randomization in their particular research

Respondents' choice of sample size and repetition seemed to depend either on what was considered to be discipline specific or on the nature of what was being tested. When variation is expected to be low then a lower sample size was used. Respondents from the fields of biochemistry and molecular biology consistently required between 3-5 repetitions. However, research the discipline of ecology requires large sample sizes where reflection of the population as a whole is required or where the rates of expected variation are naturally high. Randomization was considered by a large number of respondents to be an integral criterion in their research. The majority of respondents reasoned that randomization reduces investigator bias. An ecologist regarded randomization as a means to get a truer reflection of the population as a whole. Clearly, the need to reduce bias through randomisation is a common attribute across the majority of disciplines in the biological sciences and thus an important aspect to focus on in the training of our undergraduate and postgraduate students.

Response rates of academics

Although the overall response rate to the questionnaire was low (20%) compared to the range of 33.3 % (Watt, Simpson, McKillop & Nunn, 2002) to 56% (Nulty, 2008) reported elsewhere. What was interesting was the contrasting response rates between the two campuses. The campus where we are based, and where the investigators are known, had a high response rate of 77%, compared to a low response rate of 23% on the Westville campus where the investigators are less well known to all faculty staff. This suggests a higher rate of return for questionnaires in contexts where the investigators are better known.

What should be put into an introductory biology course

With 80% of the programs within these schools requiring BIOL 101 as a prerequisite course, these results highlighted that perhaps some consideration is required over what is necessary to adequately introduce students to the scientific process that is appropriate for such diverse disciplines in the biological sciences. The question we should be considering is: Should the teaching of hypothesis generation even be considered at the introductory level? Perhaps prior to getting students to generate hypotheses there is a need for them to adequately understand the purpose hypotheses play in advancing science. It is clear even from the responses of academics that there is disparity in distinguishing research hypotheses and statistical hypotheses and the roles these play in accordance with theories. A lack of understanding of when, how and why hypotheses and predictions are used may lead to students inappropriately applying them to specific contexts.

Considering the responses from the questionnaire regarding academics use of hypotheses and predictions, the question might be asked: ‘Why overemphasize hypothesis generation if a large proportion of the students are not going to use it later on in their careers?’. Alternatively, it should be considered that the research of those academics not currently using the hypothetico-deductive process of science would be enhanced by doing so. Perhaps specific discipline approaches to doing science should be left to the upper levels in undergraduate studies where courses are more focussed towards the majors that students are graduating in. This however, may lead once again to indoctrination of a single way of doing science. The biological sciences in the 21st century are fast becoming a multidisciplinary field of science. The emergence of many recent discoveries within this field have occurred through multidisciplinary collaborations and sharing of ideas (Ayers & Ayers, 2007). Another area that traverses disciplines is Conservation Biology which requires the development of appropriate methodologies where research focuses both on socio-economic influences as well as the complexities of ecological systems (Black & Copsey, 2014). A contemporary area of research in the Life Sciences which also uses a multidisciplinary approach is Evolutionary Developmental Biology, whereby a number of methodologies from a variety of biological disciplines, rather than a single approach, are synthesized to generate adequate explanations (Love, 2013). The way research is undertaken in each of these fields varies greatly and yet each play a significant role in the advancement of biology. Understanding the differences that lie in approaches to doing science amongst disciplines is necessary for students to be equipped to cross disciplinary boundaries and cooperate in the amalgamation of ideas to support, alter and change theories about our natural world.

One possible way to introduce this in the introductory level is to consider historical case studies and to study the different approaches employed by scientists within specific disciplines as specific course content is dealt with throughout the introductory biology course rather than having a brief introduction in the beginning. Recent research has focused on the use of biographies of scientists (Hwang, 2014); the teaching of evolution using Darwin's approach (Costa, 2003) and recounting how insulin was discovered (Stansfield, 2012) as case studies that reflect the different scientific approaches to science.

Laboratory practical experiences should not solely focus on apparatus manipulation and data collection but rather on the type of scientific approaches specific to the discipline content being studied (e.g.: evolution, molecular biology, genetics etc.). This however, would require the cooperation and coordination amongst faculty members throughout the School of Agriculture, Earth and Environmental Sciences and Life Sciences. It would be most beneficial to have academics specific to certain disciplines participating and designing learning experiences that facilitate the learning and reasoning of approaches used in their specific fields of research.

The value of this particular study is to identify areas of concern in understanding aspects of the scientific method and implementing strategies to improve in course design. One of the main attributes of this study was that it highlighted the differences in perceptions regarding hypotheses and experimental / investigation design amongst faculty members from the School of Agriculture, Environmental and Earth Sciences and Life Sciences. Perhaps an analysis of faculty's viewpoints regarding the Nature of Science might highlight further the reasons for specific responses to questions on hypotheses. Qualitative approaches to this study in the form of interviews would have possibly enabled a better understanding of academics' thoughts around the explanation of research hypotheses and alternative hypotheses. However, for this particular study which sought to determine if differences occurred in academics' views regarding the scientific method, quantitative analyses of anonymous questionnaires were sufficient to describe whether these differences occurred.

If anything this study hopefully highlighted the need for academics to seriously reflect on their own understandings of the scientific method, specifically hypothesis testing and why and how it is applied so that they are able to adequately portray these to the students they instruct. It is hoped that academics will engage in discussions around these topics and come to a consensus as to what should be taught at the first year level when introducing the scientific method at the University of KwaZulu-Natal.

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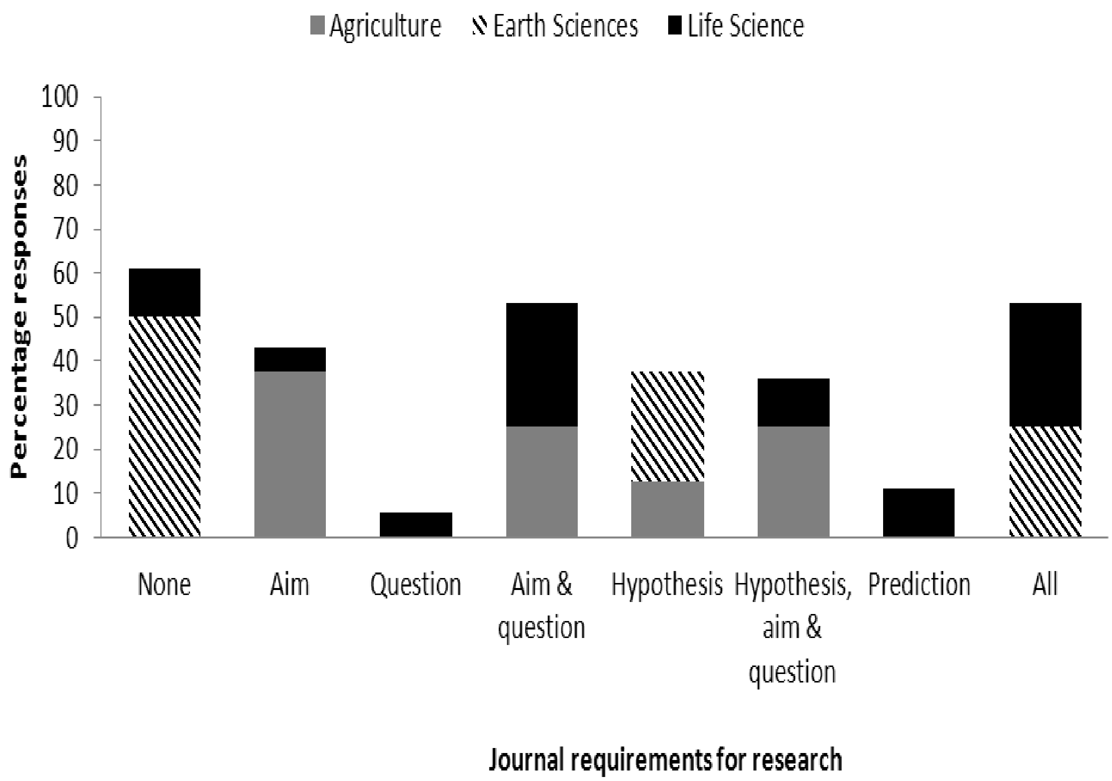

Figure 1. Overall results identifying faculty's use of hypotheses, predictions, aim or question in published research from different Schools within College of Agriculture, Engineering and Science at University of KwaZulu-Natal (n = 30).

Appendix 1: Staff Questionnaire

1 What discipline do you focus most of your research in?

□ Zoology	□ Botany	□ Ecology	□ Biochemistry
□ Genetics	□ Grassland sciences	□ Chemistry	□ Physics
□ Horticulture	□ Animal sciences	□ Microbiology	□ Physiology
□ Evolutionary biology		□ Other	

If other state what discipline: ________________________

2 Which of the following are required by journals that you publish in?

□ Hypothesis	□ Aim
□ Predictions	□ Question
□ None of the above	

3 What is your understanding of a hypothesis?

4 How does this differ from your understanding of the alternative hypothesis?

5 What type of replication or sample size do you need to conduct your research? (Why?)

6 Do you need to consider randomization in experimental design?

□ Yes □ No

Why / why not?

CHAPTER 3

Elucidating first and second year misconceptions in experimental design

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Abstract

Critical analysis of faculty's approach to undergraduate teaching of Life Sciences indicates an over-emphasis of content teaching rather than the development of scientific reasoning and critical thinking. Undergraduate courses need to engage Life Science students in the process of scientific inquiry where they are encouraged to think deeply about the process of science. One of the ways in which these cognitive skills can be developed through instruction in experimental design. Successful Life Science courses should train students to critically evaluate experimental design, statistical approaches and inferences in their entirety. Consequently, we tested first and second year Life Science undergraduates understanding of various aspects of experimental design at a South African University using an open-ended questionnaire. We found that undergraduates performed poorly in 1) producing a completely randomized design of treatments 2) describing the benefits of limiting sources of variability and 3) describing the limitations to the scope of inference for a biologist. They only showed improvement from first to second year in their ability to correctly identify treatments from independent variables. These results add to the growing body of Life Science research that indicates that undergraduate curricula are not adequately producing students with an ability to draw conclusions from hypothesis-driven experimental designs.

Keywords: *Experimental design, misconceptions, randomization, repetition*

Introduction

Good experimental design determines the quality and impact of experimental science (Lennon, 2011). However, precise scientific inferences can only be acquired if the experimental design is conceived in light of a well-defined hypothesis (Zolman, 1999). Researchers, prior to any data collection, should ensure that experiments are well-conceived plans that also consider statistical analysis in their design (Hiebert, 2007; Prosser, 2010).

Much Life Science research is flawed due to confounded experimental setups, misappropriation of statistics; or lack of clear directive hypotheses and questions prior to data collection (Zolman, 1999). Some of these issues have arisen through the introduction of powerful innovative, costly techniques producing a confidence in techniques taking precedence over appropriate statistical sampling techniques (Prosser, 2010). Biologists lacking understanding in biostatistics often consider statistics as secondary to data collection instead of it being an integral part of a studies design (Zolman, 1999). The inappropriate designs of experiments are probably embedded in a lack of good instructional training (Feldon, Crotwell, Timmerman, Stowe, & Showman, 2010). It is necessary for this to be addressed in order to prevent this from perpetuating in future generations of scientists.

Transfer of skills

Evidence of transfer of thinking and reasoning from one context to another is often considered the primary goal of education and training (De Corte, 2003; Siler, Klahr, Magaro, Willows, & Mowery, 2010). Vast amounts of money and time invested in education relies on the fact that transfer occurs, and yet there is much disparity in the literature regarding the nature of transfer (Barnett & Ceci, 2002).

Barnett & Ceci (2002) have highlighted that there are nine dimensions that play a role in the success of transfer. These include aspects related to content to be transferred as well as to context from and to which skills are transferred (Barnett & Ceci, 2002). Much learned knowledge and skills are grounded within the situation in which they were learned (Khishfe, 2012). The manner in which knowledge and skills are learned will influence how transfer occurs to new contexts (Mayer & Wittrock, 1996). Consequently, specialized undergraduate science academic programs require experiential training that appropriately prepares graduates for the world of academia and beyond.

Learning environment

Researchers operating in the field of experimental science strive to interpret important questions by appropriately designing treatments that enable accurate and valid measurements which produce undisputable data and integrate strong inferences with current knowledge (Zolman, 1999). This is not always reflected in the training of science undergraduate and graduate students. The American Association for the Advancement of Science (AAAS, 2010) has challenged undergraduate institutions to transform their classrooms to more accurately mirror the Life Sciences practiced at postgraduate and research levels (Woodin, Carter, & Fletcher, 2010).

Too often undergraduate science courses provide practical or experimental experiences whereby procedural details are already prepared and provided (Brownell, Kloser, Fukami, & Shavelson, 2012; Pollack, 2010). Students are rarely required to develop their own experimental procedures or critically evaluate experimental designs of others (Pollack, 2010; Zolman, 1999). The reason for this is to ensure that experiments can proceed within a specified time period; however, it produces a shortfall in students understanding of experimental design (Hiebert, 2007). When students are not involved in the intricate planning of experiments they are often oblivious to the thought processes and detail concerned with producing accurate and appropriate designs (Pollack, 2010).

A deep-rooted misconception that many science students have is the erroneous separation of experimental design from statistics (Zolman, 1999). The result of this misconception is that many postgraduates and naïve Life Science researchers undertaking research often complete data collection prior to considering suitable data analysis procedures (Zolman, 1999). Too often statistical approaches are not included or not explicit in the design of undergraduate laboratory experiments. This perpetuates the students' mistaken understanding that the collection of data is a separate entity to statistical analysis (Hiebert, 2007). This misconception may also have arisen unintentionally through inappropriately designed curricula. Students studying an undergraduate degree in science are usually required to participate in at least one statistical course. Although this is essential in understanding statistics, practical experiences within these courses often deal with previously generated data. This may develop the incorrect impression that statistical models need only be considered after data collection and does not play a role in the design of experiments (Zolman, 1999).

The lack of consideration of statistics in the planning stages of an experiment eliminates a whole dimension of experimental design. The way in which an experiment is set up, repeated, and randomized, is rooted in the statistical model chosen prior to data collection. Data collected arbitrarily will result in inaccurate and invalid measurements and any inferences based on this data are likely to be the result of chance (Lennon, 2011; Zolman, 1999).

Previous research

Undergraduate science students may be able to formulate hypotheses but few are able to develop ‘testable’ hypotheses (Pollack, 2010). Within the field of experimental science there is the assumption with a testable hypothesis that there has been careful consideration of sampling techniques, treatments, controls and statistical analysis prior to data collection. Statistical inference of data can however be detrimentally affected if decisions concerning sampling are arbitrarily selected (Anderson, 2002), or if these considerations are not adequately made.

Undergraduate science students struggle to rationally develop appropriate experimental designs (Hiebert, 2007). For students to master skills in experimental design they must “be able to identify system variables that can affect an experiment and understand the impact these variables have on experimental results” (Grunwald & Hart, 2010). Grunwald & Hart (2010) found that many undergraduate science students struggled with the skill of identifying experimental variables that were probable causes of error.

Most science students know that an experiment should have a control but most undergraduates do not really know what a control is and how to design a control in an experiment (Hiebert, 2007). Ask any student how individuals should be separated into treatment groups and they will likely answer ‘randomly’ but many are unsure of how to do this (Hiebert, 2007). Many students know that as sample size decreases sampling error increases but few students know the reason why (Hiebert, 2007). Furthermore, many students have an understanding of statistics but do not know which statistical test to use when comparing two treatment groups (Hiebert, 2007). These results indicate that students perhaps have a theoretical understanding of aspects of experimental design but have not been taught it practically or at least not in its entirety. There is a need to mentor students in understanding that an experiment is a well-conceived plan which considers data collection, data analysis and data interpretation all in relation to a testable hypothesis.

Purpose of the study

Consequently, the purpose of this study was to determine whether undergraduate biology students have difficulty with reasoning in various aspects of experimental design. The focal questions concentrated on evaluating students' ability to (1) identify treatments in a biological experiment; (2) randomly assign experimental units to treatments; (3) Co-ordinate explanations with evidence; (4) relate inferences to the research question and (5) provide an explanation of limitations to the scope of inference for an investigation. We tested these focal questions with two consecutive years of first year students (to examine consistency in responses between years), and reassessed the first cohort once they were in second year (to assess change in responses as they progressed within their undergraduate degree). We tested whether students in different cohorts of the same course would score similarly within their first year, showing poor scientific reasoning levels. We also examined whether a cohort of students would improve scientific reasoning during their second year of undergraduate study. Students who enroll in the BIOL 200 course in their second year are given a comprehensive manual which covers the process of the scientific method and approaches to statistics as part of the course handouts. We thus expect to see an improvement in students' scientific reasoning skills from first year to second year.

Methods

Science students' approach to experimental design was investigated in two undergraduate courses in the School of Life Sciences at the University of KwaZulu-Natal (UKZN), Pietermaritzburg campus to determine whether there were any flaws in student reasoning about biological experiments.

Students' scientific reasoning in experimental design was evaluated using open-ended questions on a shrimp experiment from a published Advanced Placement Program® (APP®) item (Appendix 1). Ethics clearance for the project was granted by the University of KwaZulu-Natal ethics committee.

Students from first year Biology 101 (BIOL 101) and second year Biology 200 (BIOL 200) participated in this study as part of their normal course requirements in 2011 and 2012. Questionnaires were presented to students as an open-book task in a controlled environment with no advanced notice. Examining responses over two years, in two separate cohorts, enabled assessment of reliability of our results, and consistency in scientific inference levels in first year students. Second year students had completed the BIOL 101 course as a prerequisite to entering BIOL 200. This enabled the evaluation of individual students gain in scientific reasoning from first year to second year. At UKZN, biological science (general stream) students are required to take Statistics 130 (STATS 130) in their first year running concurrently with BIOL 101 (UKZN College of Agriculture, Engineering & Science 2012 Handbook pg. 73 & pg. 344).

Data analyses

Analyses focused on various kinds of evidence of students understanding of biological research skills. Mixed methods design comprising both quantitative and qualitative data analyses was used to evaluate students' scientific reasoning ability. Marks for each question were allocated according to a scoring rubric (Table 1) that we developed out of the range of answers received, and these were analyzed quantitatively, in addition to an analysis of total test score. The types of responses to the questions were characterized qualitatively to determine students' approach to experimental design and the typical misconceptions in students' reasoning about biological experiments. The number of individuals answering within each characterized category was counted and then calculated as a percentage. These analyses were represented graphically showing the percentage of individuals in each coded category across and between years. Both quantitative and qualitative analyses provide grounds for remedial strategies relevant to students' biological research skills.

Statistical analyses

Student performances on individual questions were compared between years using Analysis of Variance (ANOVA). Repeated Measures Analysis of Variance (RMANOVA) with post-hoc Tukey tests were used to determine whether there was any significant improvement in students understanding from first year to second year in the different aspects of experimental design tested for. All analyses were conducted using STATISTICA Version 7 (Statsoft, Tulsa, Oklahoma).

Results

Analyses of the total questionnaire scores achieved by students for the questionnaire revealed that there was no significant difference in performance between the first year cohorts of 2011 (n = 415) and 2012 (n = 319) ($F_{1,\ 732}$ = 0.635, p = 0.426) as well as no significant difference between the second year student cohorts of 2011 (n = 39) and 2012 (n = 47) ($F_{1,\ 84}$ = 3.794, p = 0.060). We therefore combined the two cohorts results for further analysis.

First and second year responses to focal questions in the questionnaire

The combining of first year cohorts and second year cohorts generated the following results with regards to individual questions. Although students performed poorly in all four questions, both first year and second year students performed better in Question A concerned with the identification of treatments. First year students scored a mean of 1.39 ± 0.04 SE out of 4 (n = 734) whilst second year students scored slightly better with a mean of 2.17 ± 0.15 SE (n = 86).

Both first years and second years performed the poorest with regards to Question B concerned with the randomization of treatments. With first year students scoring a mean of 0.40 ± 0.20 SE out of 3 and second year students scoring a mean of 0.29 ± 0.09 SE. First and second year students performed similarly for Question C regarding the advantages of using one type of shrimp in an experiment (1^{st} year students mean = 0.89 ± 0.04 SE; 2^{nd} year students mean = 1.08 ± 0.12 SE out of a score of 4). In response to Question D which sought an appropriate statistical disadvantage for using only one type of shrimp the results reflected similar scores for both first year students (mean = 1.32 ± 0.15 SE) and second year students (mean = 1.45 ± 0.18 SE) out of a score of 4.

Comparing mean total score by students revealed second year students achieved a slightly higher mean than the first year students (2nd year total mean = 5.00 ± 0.31 SE; 1st year total mean score = 3.52 ± 0.09 SE).

A comparison between scores obtained from a single cohort tested in both 2011 and 2012

There was no significant difference in total test scores when following a cohort of students from first year in 2011 to second year in 2012 (n = 25) ($F_{1, 24}$ = 0.157, p = 0.696) (Fig. 1). Individual students' scores were not significantly different between years for question B ($F_{1, 24}$ = 0.600, p = 0.446), question C ($F_{1, 24}$ = 0.723, p = 0.404) and question D ($F_{1, 24}$ = 3.827, p = 0.062). However, individual students improved their score significantly for question A ($F_{1, 24}$ = 10.061, p = 0.004). (Fig. 1).

Undergraduate students' conceptions of aspects of experimental design

Students at undergraduate level struggled to identify treatments in a biological experiment. Less than 10% of first year students were able to correctly identify treatments (Fig. 2a). However, about 60% were able to identify independent variables (Fig. 2a). By second year about 35.9% in the 2011 cohort and 36.2% in the 2012 cohort were able to identify treatments accurately but still 46.1% of 2011 cohort and 40.4% of 2012 cohort mistakenly identified independent variables as the treatments.

The questionnaire also highlighted students' difficulty in randomly assigning experimental units to treatments. Less than 5% of first year students were able to show any form of randomization (Fig. 2b). Second year students also exhibit a lack of understanding of randomization with 76% of students in 2011 and 93% in 2012 showing an absence of any form of randomization. The majority of first and second year undergraduate students failed to identify and understand the role of variance control through the use of a single study species (Fig. 2c). Surprisingly, less than 3% of these students, across the four cohorts tested, correctly identified this. The majority of students also lacked the ability to reason why using a single species in an experiment would be a disadvantage. Between 25.5% (second year students 2012) and 36.4% (first year students 2011) of the students recognized that only one species of shrimps was measured but failed to explain how this was a statistical disadvantage (Fig. 2d). Between 46.2% and 61% of all undergraduate students across all years failed to recognize the disadvantage that testing only one species limits the extent of inference.

Discussion

First year students, across two separate cohorts, showed consistently poor scientific reasoning levels, highlighting several fundamental gaps in their ability to correctly understand elements of experimental design. In addition, advancement to second year level, with additional pre-requisite courses that include theoretical input on experimental design, led to very little improvement in scientific reasoning levels in the same students.

Confidence is placed in scientific claims because they are largely perceived as being reliable, and this reliability lies in the manner in which scientific claims are verified (Gower, 2012). Scientific claims are dependent on rational, objective, reliable approximations of reality (Gauch, 2003). Do our undergraduate students fully understand the vital role that good experimental design plays in advancing science through experimentation? Development of the next generation of scientists requires training in the critical evaluation of experimental design in order that future inferences in science are made with confidence.

Open-ended questioning formats provide evidence of not only what students know but also an understanding of students reasoning (Parker, Anderson, Heidemann, Merle, Merritt, Richmond, & Urban-Lurain, 2012). The questionnaire used in this study enabled an evaluation of students' critical reasoning skills in experimental design. All four questions highlighted students' relatively poor understanding of the intricate intertwining nature of research question, design, reliable data collection and statistical inferences.

The role of randomization

About 95% of all undergraduate students tested failed to randomize treatments appropriately. This highlights students' lack of understanding of the role of randomization in controlling for extraneous variables. Some students showed some knowledge of the purpose of randomization but were incapable of practically randomizing treatments in an experimental design. Undergraduate students that continue their science careers by entering postgraduate programs are required to write theses of publishable results based on testable hypotheses, good experimental design and analyses of data collected under the supervision of mentors. Understanding of the role of controlling for confounding factors and extraneous variables through randomization is essential in obtaining reliable, accurate approximations of the truth.

Improvement in scientific reasoning from first year to second year level

Given that second year students enrolled in BIOL 200 receive both course materials and more comprehensive instruction on the process of science and statistics it was expected that students would have better knowledge of the role of statistics in experimental design by the end of the course. However, there was no significant improvement in students' scores on the shrimp questionnaire from first year to second year. The only improvement that occurred was their ability to identify treatments from the independent variables being tested. Critical consideration and reasoning of reducing variability, controlling for extraneous factors and producing inductive inferences tested in the remaining questions was shown to be largely absent in most first and second year undergraduate science students tested. This appears to not be the result of a lack of theoretical knowledge surrounding the importance of these factors in experimentation but rather a lack of experience in the practical application of the knowledge. The positive impact of mentored research experiences on the process of learning at undergraduate level is further explored in Chapter 6.

Knowledge and reasoning skills in experimental design?

“Successful undergraduate programs in the Life Sciences are those that graduate students who are able to ‘think like a scientist’” (Coil, Wenderoth, Cunningham & Dirks, 2010), not those that produce students who are able to regurgitate scientific facts. Knowledge of, and understanding of factual content matter is an essential prerequisite to critical thinking skills (Kishbaugh, Cessna, Horst, Leaman, Flanagan, Neufeld, & Siderhurst, 2012; Momsen, Long, Wyse, & Ebert-May, 2010). However, content gained through rote-learning will not be meaningfully integrated into students’ conceptual framework without the repertoire of skills needed for this to take place (Coil et al. 2010; Feldon et al. 2010). This is particularly difficult in a domain where there is an ever increasing expansion of fragmented content and complexity in its multidisciplinary nature, and interconnectedness with other domains (Coil et al. 2010; Labov, Reid, & Yamamoto, 2010). It is essential that undergraduate science students don’t just rote-learn scientific content knowledge but rather develop the cognitive skills needed to understand how that knowledge was constructed. This will enable them to master the acquisition of content at an early stage in their biological career. It will also enhance their understanding of how and why that knowledge became known as a scientific claim.

Evidence suggests that explicitly teaching undergraduate students science process skills at the beginning of their degrees may strengthen understanding of science content (Coil et al., 2010). It is important as faculty to understand what explicit instruction entails. D'Costa & Schlueter (2013) have implemented a scaffolded instruction approach to their training in scientific skills. They believe that "students should not be exposed to open inquiry until they have sufficient experience with the lower levels of inquiry" (D'Costa & Schlueter, 2013, pg. 18). This is achieved by a gradual progression from "structured inquiry" to "guided inquiry" to "open inquiry". As useful and successful as this instruction is, one must still ensure that this type of instruction does not instil a cookbook recipe way of doing science.

At the other end of the spectrum is instruction through "discovery" whereby students discover for themselves the strategy for solving domain problems (Feldon et al., 2010). Although this may instil interest in research in the Life Sciences it undermines the scientific process. It will also likely lead to repercussions later in the student's scientific career if there is a lack of understanding of, and application of, a testable hypothesis or question, controlling of extraneous variables and appropriate use of statistical models to provide accurate inferences based on experimental setups. Both of these instructional training techniques have advantages and disadvantages. Successful training will be achieved only if instructors understand and implement development of scientific reasoning skills throughout the training process.

Technique training or skill development?

"It is in the investigative mind that we do science; the laboratory offers only an opportunity to test scientific hypotheses through predictions (the products of the mental process that constitutes science)" (Karsai & Kampis, 2010). Traditional laboratory practical sessions do not portray science from this perspective. Many laboratory experiences involve students at a low intellectual level leaving students with a naïve understanding of the thinking processes involved in investigations and the significance of experimental results obtained (Brownell et al., 2012; Hume & Col, 2008). Too often investigations performed by students in their undergraduate laboratories require 80% doing (mostly in the form of following a step-by-step manipulation of apparatus) and 20% thinking instead of the other way around. Students spend most of the time trying to master specific techniques or the use of specific apparatus rather than focusing on the why part of the investigations (personal observation, Baker & Dunbar, 2000). The outcomes of these set-piece practical exercises are clearly to determine what students are able to do but the development of students understanding and reasoning of why they are supposed to do it is overlooked (Barnard & McGregor, 1993).

Designing of constructive instruction through practical experiences in undergraduate education requires a careful consideration of the purposes one has for these experiences. Is the purpose of these laboratory practical exercises to introduce students to specific techniques, procedures and use of equipment, or is it to develop thinking and reasoning skills through the medium of the use of these techniques, procedures and equipment? Questioning plays a significant role in ensuring that the latter is being developed in practical experiences. Thorough assessment of questions devised to elicit students understanding of scientific process skills should focus on reasoning (why and how questions) rather than identification (what questions).

The goal of instruction is to enable students to transfer knowledge and skills to future situations (Siler et al., 2010). Training in the use of a photometer will not be helpful for students when investigating the thermoregulation of a specific animal for example, however reasoning skills associated with the controlling for confounding factors, repetition and selection of appropriate statistical approaches are skills that students will be able to transfer to new contexts of investigation.

Detrimental aspects of practical experiences

Poor instruction has been viewed as one of the primary obstacles to learning in science majors (Feldon et al., 2010). Experimental design is a skill which cannot be grasped through abstract teaching but rather through experiential learning (Stafford, Goodenough, & Davies, 2010). It is thus essential that if students are exposed to experiential learning then it must accurately reflect the process of scientific investigation both theoretically and practically.

Scientists regularly critically evaluate, from numerous possibilities, the best approach to investigate a scientific problem and frequently deal with open-ended problems throughout the inquiry process (Feldon et al., 2010; Hume & Col, 2008). Scientific inquiry is however, more often than not packaged and portrayed as a straightforward, unproblematic practical exercise in the curriculum (Hume and Col, 2008).

The need to teach experimental design in large-scale undergraduate classes poses problems due to both time and cost constraints. As a result, the "essence of scientific inquiry may get diluted, displaced and distorted" (Chin & Chia, 2006, pg. 45) in the process. This is particularly the case when the cost of materials restricts the number of true replicates students can produce in their investigations, and instead rely on replicates performed by different individuals, thereby increasing the inter-operator variability, particularly in first year students who are relatively inexperienced in scientific procedures (Stafford et al., 2010). Students are therefore being taught theoretically about the necessity of reducing variability through large sample sizes and sampling error but in the practical element of their course this is not portrayed as important.

Statistics in experimental design

Time constraints often mean that statistical analyses in undergraduate practical courses are kept to a minimum with descriptive statistics being the primary tool focused on or worse yet statistics evaded altogether. However, investigations lacking appropriate inferential statistics produce meaningless results and suspect conclusions (Pollack, 2010; Prosser, 2010).

Equally so experimental design which disregard statistical approaches prior to data collection are likely to produce elaborate interpretations of data that were most likely produced by chance (Zolman, 1999). Failure to include statistics in undergraduate practical experiences may lead to the incorrect perception that statistics is not an essential element of experimental design.

Of all the sciences, Life Sciences students should understand the implications for not using appropriate statistics. Too often this responsibility is delegated to concurrent statistical courses (Zolman, 1999). These courses often work with abstract spreadsheets of data which have little biological significance to students. Students need to understand the biological variability within the natural world in the domain of their studies, and should be trained in the appropriate use of inferential statistics so that they are capable of making convincing statements and confident conclusions that the relationships observed in their results are real and not just due to natural variability (Anderson, 2002; Prosser, 2010).

Alternative approaches used to improve students understanding of experimental design

Gottesman & Hoskins (2013) use an approach to training scientific process skills that lacks a laboratory component. The CREATE (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment) strategy seeks to promote open-ended discussion, creative design, critical analysis, logical reasoning of interpretations and the significance of findings characteristic of doing science (Gottesman & Hoskins, 2013). This method uses analyses of primary literature to improve students' ability to critically evaluate relevant science content. It has been argued that encounters with primary literature should be focused at higher-levels due to inexperience in scientific reading of lower level undergraduates (Gottesman & Hoskins, 2013; Round & Campbell, 2013). However, mentoring through open discussions and experience gained over a number of years in undergraduate courses ensures that graduates do not enter postgraduate level scientifically illiterate and lacking the ability to critically evaluate past and present scientific claims.

Conclusion

This study showed that first and second year undergraduate Life Science students at a South African University had poor understanding of the fundamental basics of experimental design. Generally, they were unable to produce completely randomized design of treatments, describe the benefits of limiting sources of variability and describe the limitations to the scope of inference for a biologist.

These findings concur with recent research suggesting that undergraduate courses at university level are too content focused and are not transferring skills regarding the practice of Life Science encompassing the controlling of extraneous factors through randomization and repetition (Grunwald & Hart, 2010; Prosser, 2010). They also lack understanding of the significance of statistics in the design process and how one can reduce bias through good experimental design. Many students have theoretical knowledge of controls, treatments, randomization, repetition, sample size selection but are unable to implement this practically in the design of experiments.

We recommend the undergraduate courses move away from a cook-book recipe approach to laboratory practical exercises and instead incorporate critical thinking elements to these practical experiences that challenges Life Science students to evaluate factors that introduce variation, how design influences results, accurate use of statistical approaches, whether inferences are weak due to bad design, whether hypotheses have been adequately tested and suggest alternative approaches to testing them to infer or deduce logical conclusions. Alternatively, providing opportunities for students to critically evaluate the methodology given to them by providing questions that probe understanding. This could follow either at the end of a practical session or at a subsequent tutorial would allow further development of critical thinking and evaluating skills, while retaining the practical application of “cookbook” style sessions for large class sizes.

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Table 1: Scoring rubric of marks allocated to questions testing for treatment identification, randomization and explanations of variability and inferences in a questionnaire given to first, second year and postgraduate Biology students at the University of KwaZulu-Natal University, South Africa in 2011 and 2012.

Question A: Identification of treatments	Question B: Describing a randomized design
4 – Treatments correctly written	3 – Randomized treatments correctly
3 – Identified independent variables and not treatments	2 – Attempted to randomize but treatments inaccurate
2 – Identified independent variables and control variables	1 – Showed no randomization
1 – Minimal response	
Question C: Statistical advantage (reduced variability)	**Question D: Statistical disadvantage (limiting scope of inference)**
4 – Eliminating variation so that only the effect of treatments observed	4 – Linking inference to aim of experiment
3 – Eliminating variation but no explanation	3 – Identifies no other species measured but not linking to aim
2 – Accuracy of results but no explanation	2 – Only tiger shrimps measured but no explanation
1 – Incorrect understanding	1 – Incorrect understanding

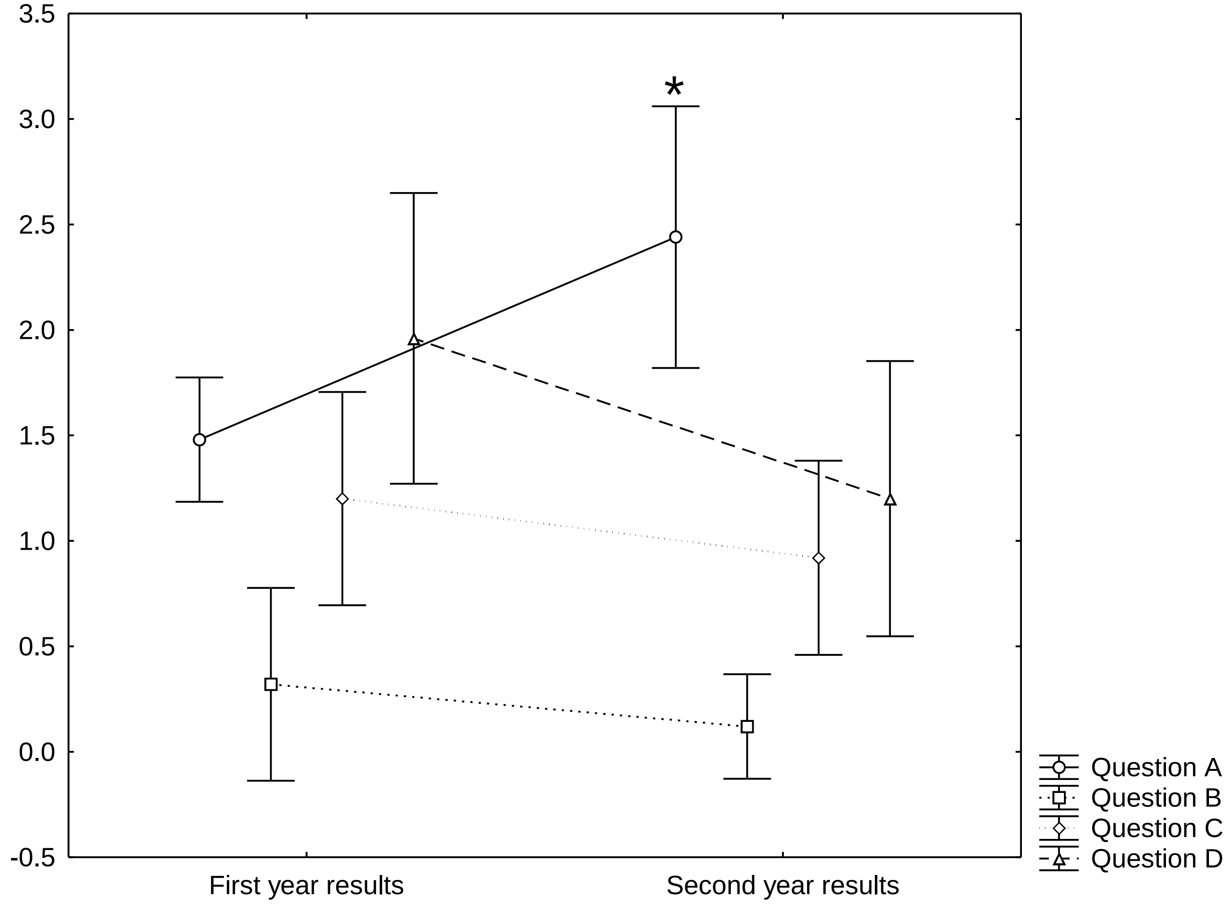

Figure 1: University of KwaZulu-Natal undergraduate Biology students' (n = 25) improvement in mean ± SE results from first year to second year for a single cohort for questions question A (treatment identification), question B (randomization), question C (explanation of variability) and question D (explanation of inference). * indicates significant difference between first year and second year results for a question.

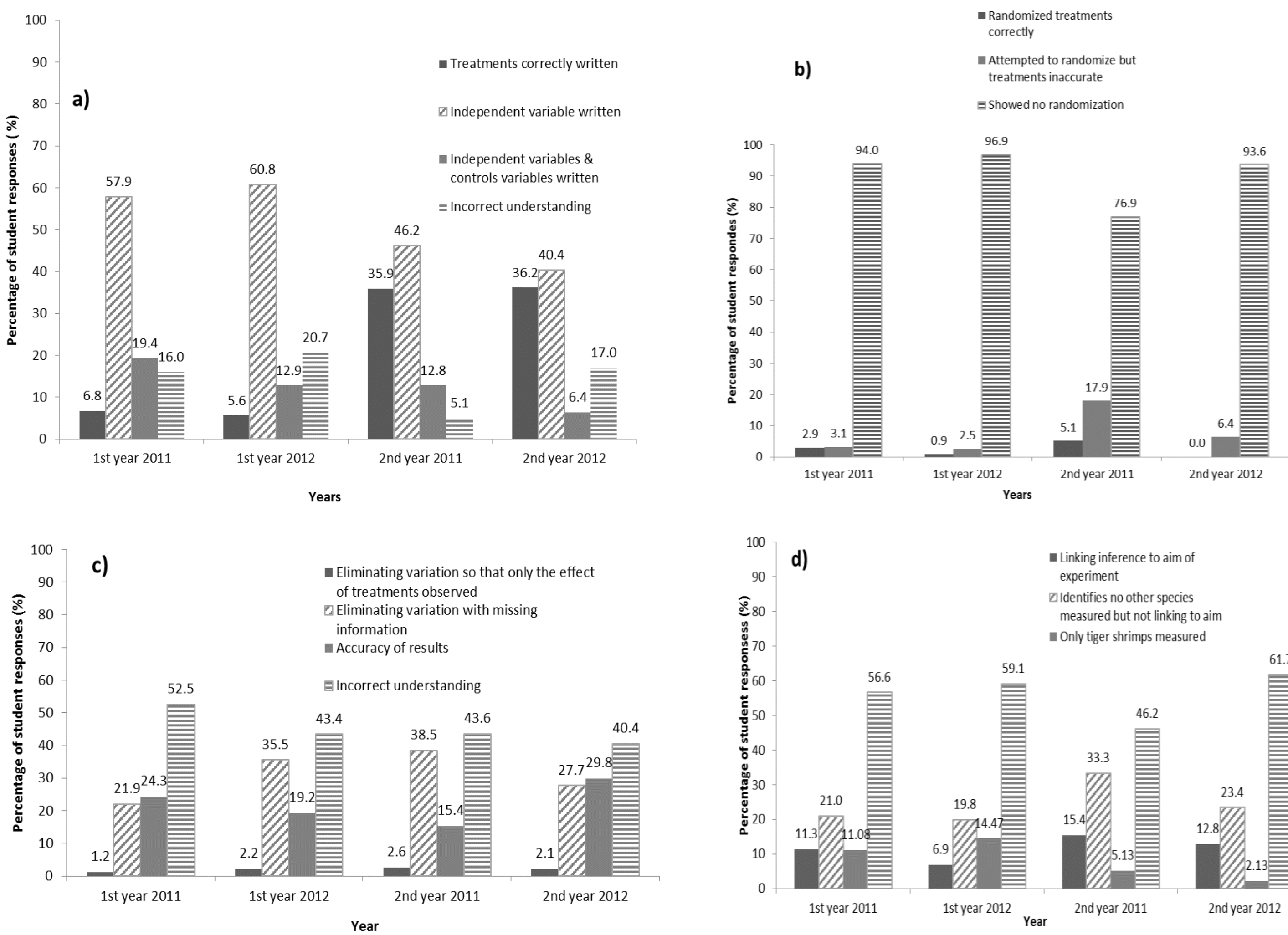

Figure 2a-d: Percentage of undergraduate and postgraduate Biology students (2011 first year students, n = 414; 2011 second year students, n = 39; 2012 first year students, n = 319; 2012 second year students, n = 47) categorized into conceptions in response to questions pertaining to a) treatment identification b) randomization c) variation and d) inferences at the University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Appendix 1: Shrimp Questionnaire

Background Information

A biologist is interested in studying the effect of growth-enhancing nutrients and different salinity (salt) levels in water on the growth of shrimps. The biologist has ordered a large shipment of young tiger shrimps from a supply house for use in the study. The experiment is to be conducted in a laboratory where 10 tiger shrimps are placed randomly into each of 12 similar tanks in a controlled environment. The biologist is planning to use 3 different growth-enhancing nutrients (A. B. and C) and two different salinity levels (low and high).

a. List the treatments that the biologist plans to use in this experiment.

b. Using the treatments listed describe a completely randomized design that will allow the biologist to compare the shrimps' growth after 3 weeks. (You may use a Figure or Table).

c. Give one statistical advantage to having only tiger shrimps in the experiment. Explain why this is an advantage.

d. Give one statistical disadvantage to having only tiger shrimps in the experiment. Explain why this is a disadvantage.

CHAPTER 4

What are our assessments telling us? Exploring assessments of scientific method questions in a first-year biology cohort

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Abstract

Faculty staff have been challenged by science educators to change their approach to teaching in order to more accurately reflect the practice of biology. Meeting these challenges requires the critical analysis of current teaching practices and adjustment of courses and curricula through curriculum reform. Assessments play a vital role in providing evidence of effective instruction and learning. Student responses from two formative tests and one final summative examination for an undergraduate biology cohort (n = 416) in a South African University were analyzed both quantitatively and qualitatively to determine students understanding of aspects of the scientific method. Quantitative analyses revealed that the majority of first-year undergraduate students at the end of an introductory biology course were able to identify hypotheses and dependent and independent variables correctly. However, qualitative analyses indicated that sometimes students confuse hypotheses with predictions and are unable to identify independent variables correctly.

Critical analyses of the assessments using the Blooming Biology Tool revealed that assessment design can considerably influence student results. It is essential that clear objectives and competencies are set at the outset and that there is a synergistic relationship between instruction and assessment. Assessment design requires careful consideration of content being covered as well as cognitive skills being tested throughout the course.

Keywords: *Assessment, scientific method, cognitive skills, Biology, hypothesis identification, variable identification*

Introduction

The traditional approach to teaching an introductory biology course focuses on the presentation of faculty-centered lectures accompanied by laboratory sessions to provide students with "hands-on experiences" (Cocking, Mestre & Brown, 2000; Moravec, Williams, Aguilar-Roca & O'Dowd, 2010). Assessment of these courses includes formative assessments in the form of tests and final summative examinations to determine students' acquisition of knowledge presented in lectures and textbooks (Downs, 2009; Williams et al., 2010).

The American Association for the Advancement of Science (AAAS, 2010) calls for rethinking and redesigning of curricula and courses that more accurately reflect the science practiced (AAAS, 2010; Woodin, Carter, & Fletcher, 2010). The practice of biology is more than just knowledge of scientific facts. Equally important, itis a process whereby scientific claims are generated and critically assessed through a scientific process. It is important that even at introductory level courses, an appreciation for all aspects of the scientific process is instilled in undergraduates (AAAS, 2010).

In an attempt to incorporate skills required for scientific inquiry, many institutions include the scientific method as an introductory section and most first year textbooks have an introductory chapter on the scientific method (Spiece & Colosi, 2000; personal observation). It is important to introduce to students how scientists generate knowledge of the natural world, but this is often presented to students theoretically and not always practically (Brownell, Kloswer, Fukami, & Shavelson, 2012), and is often done separately from the rest of the course material, with little to no linkage of how it relates to the rest of the course. It is also often presented as a simplified "one size fits all" method, rather than a complex multi-faceted field. Laboratory sessions at undergraduate level are designed to give students 'hands-on' experience, yet often undermine the goals they are designed to achieve (Karsai & Kampis, 2010). Isolated recipe-type experiments may introduce a technical skill or method but does not provide opportunity to develop theorizing, generating of questions, hypothesizing, critical analysis and reasoning (Brownell et al. 2012), all of which are necessary skills for a developing scientist.

Worldwide it is generally noted that adjustments in faculty science teaching approaches need to take place (Brownell & Tanner, 2012). Historically, curriculum development was achieved through faculty staffs' intuition, experience and knowledge of subject content (Anderson & Rogan, 2011). However, there needs to be a shift in rethinking about what and how science is taught. For too long faculty have clung to the teaching practices that mirror how they themselves were instructed (Cocking et al., 2000). This may be a result of ignorance of pedagogical strategies or perhaps it is the greater importance they place on content knowledge rather than on skills development *(*Brownell & Tanner, 2012*)*. As scientists who practice and understand the relevance of research, there is no excuse for not using the findings presented by educationalists to inform their teaching. It is essential that faculty not only is proficient in their subject content knowledge but that they are also educated in the latest research of teaching and learning in their fields (Labov, Reid, & Yamamoto, 2010).

The AAAS recommends that instructors move away from presenting “all the facts” towards clearly outlining learning outcomes which include competencies to be developed in curricula and courses (AAAS, 2010). Competencies refer to the skills required for students to become proficient communicators and practitioners in their field (AAAS, 2010). Outcomes outlined at the outset of a course or curriculum provide both focus and direction for teaching instruction and assessment (Anderson & Rogan, 2011)**.** This then ensures a “backward” approach to curriculum design whereby outcomes inform assessments which in turn informs instruction (Wiggins & McTighe, 2005). When designing biology curricula in undergraduate courses, one should take into consideration the end goal of an undergraduate degree. In other words, what are the expectations required at postgraduate level. Postgraduates require skills in observation, generating questions and hypothesizing, experimental design, generating and critically analysing of data, reasoning and effectively communicating their inferences to the scientific community (Kishbaugh, Cessna, Horst, Leaman, Flanagan, Neufeld, & Siderhurst, 2012; Pellegrino, 2012). The development of these skills is essential in the undergraduate degree and should start to be instilled even in the introductory courses (AAAS, 2010)**.**

Alignment of assessments with instruction

Assessments which do not reflect instruction in the classroom, and vice versa, leads to an undermining of the course or curriculum and any data generated from these assessments are meaningless (Crowe, Dirks & Wenderoth, 2008). It is essential that there is a synergy between instruction and assessment.

Prior to the designing of assessments, it is imperative that the purpose of the assessment is made clear. There are a number of uses of assessments. Some assessments are primarily designed to improve learning (Yorke, 2003). These assessments are more commonly known as formative assessments**.** Summative assessments are generally designed to assess whether outcomes have been achieved at the end of a course or curriculum (Williams & Wong, 2009). Although both formative and summative assessments primarily focus on improving learning, they also have a role in informing instruction (Yorke, 2003). Another form of assessment is instruction-sensitive assessments which focus on the quality of instruction (Ruiz-Primo, Li, Wills, Giamellaro, Lan, Mason, & Sands, 2012). All assessments, if designed appropriately, can provide evidence of both teaching and learning and thus play a role in curriculum development (Anderson, 2007).

Essential criteria in assessments

It is imperative that assessments are critically analyzed to assess whether they are achieving the purposes for which they were designed (Crowe et al., 2008). This places enormous responsibility on faculty staffs' choice of assessment tools and the careful consideration of the structuring of individual questions.

Assessment tools can adopt a variety of forms such as multiple-choice questions, short answer questioning, open-ended questions and essay-type and interview questioning (Parker, Anderson, Heidemann, Merrill, Merritt, Richmond, & Urban-Lurain, 2012). Each assessment tool may elicit different responses from students and test their understanding in a different manner (Pellegrino, 2012). Unfortunately, the type of assessment tool is often chosen with the purpose of ease of administration rather than its potential to adequately evaluate students' achievement (Momsen, Long, Wyse, & Elbert-May, 2010), or to determine if the learning outcomes of the course have been achieved.

The structuring of questions is an equally important aspect of designing assessments. Students come from a variety of different socioeconomic and academic backgrounds which may influence the way in which students interpret and respond to questions (Turkan & Liu, 2012). In English-medium Universities there is often an assumption by faculty that students have acquired language proficiency in communicating scientific ideas in test and examination situations (Solano-Flores, 2006). However, English second language students may be at a disadvantage if the area of language is not considered in formulating questions in assessments. (Downs, 2006). In other words, questions need to be structured in such a way that they isolate the factor being tested from linguistic and cultural influences (Turkan & Liu, 2012).

Assessing scientific method and critical thinking skills

In the biological sciences much research uses the hypothetico-deductive approach where inductively developed theories are altered or changed through critical testing of hypotheses through a deductive process (Guthery, 2007; Quinn & Keough, 2002). Hypothesis formulation is the essential forerunner of an investigation. The process of testing, collection of data and statistical analysis rely on the rational formulation of the hypothesis (Quinn & Keough, 2002).

It is also essential that experimental design has been well thought out. The key to being able to make strong inferences is to reduce the amount of uncertainty (Anderson, 2008). This can be achieved through the application of good experimental design taking into account factors such as randomization, repetition, sample size, controls, control of variables and confounding factors (Anderson, 2008).

If the goals of science courses and curricula are to nurture students to become effective scientists in their field of study, then these skills need to be developed in instruction and reflected in the assessments designed to test the achievements of these skills. The skills required by scientists go beyond the ability to recall and understand information but involve critical thinking (Momsen et al., 2010). Assessments need to be designed in such a manner as to illustrate students' attainment of scientific skills and not solely content knowledge (Bissel & Lemons, 2006). Sadly, though, although many faculty staff acknowledge the need to develop these skills in their students, very few adequately assess them in their courses (Ebert-May, Batzli & Heejun, 2003). An important step in assessment design is to critically evaluate whether a particular question or assessment tool is testing the cognitive skills for which it was designed.

The task of designing useful assessments to test critical thinking is not that straightforward. Crowe et al. (2008) have developed an assessment tool based on Bloom's Taxonomy analysis often used by educationalists (Kishbaugh, 2012). This Blooming Biology Tool (BBT) is available to assist biology faculty staff in assuring that their assessments are testing for these critical thinking skills. Bloom's taxonomy has six levels of cognition. The first two levels are known as lower-order cognitive skills (LOCS), namely knowledge and comprehension (Kishbaugh, 2012). The following four levels are known as higher-order cognitive skills (HOCS) and these fall into the realm of scientific critical thinking. Higher-order cognitive skills include application, analysis, synthesis and evaluation (Crowe et al., 2008).

An incorrectly structured question intended on testing higher-order thinking may in fact only be testing recall or understanding (Anderson & Rogan, 2011). This places enormous responsibility on faculty staffs' choice of assessment tools and the structuring of individual questions. Although multiple-choice questions are relatively easy to grade they are less valuable in testing HOCS than open-ended questions, essays and oral interviews (Momsen et al., 2010). Questions that are more labour-intensive can often provide greater insights into students understanding and misconceptions (Pelaez, Boyd, Rojas & Hoover, 2005). The appropriate implementation of assessments in the classroom can be an invaluable tool to inform both learning and instruction within courses and across curricula (Anderson, 2007). The implementation of appropriate methods for assessing and analysing classroom data can assist faculty staff in ascertaining student misconceptions and improving instructional strategies (Elbert-May et al., 2003).

Research to date on students' understanding of scientific method

Previous research has identified a number of aspects of the scientific method that students struggle with. For example, students have been known to have difficulty in differentiating between hypotheses and predictions (McPherson, 2001; Schwagmeyer & Strickler, 2011). D'Costa & Sclueter (2013) showed that through course adjustments that students improved their ability to create hypotheses. They found that students could correctly identify controls and dependent variables; however, students faced difficulties with identifying independent variables and controlled variables (D'Costa & Sclueter, 2013).

Purpose of study

This study focused on a cohort of introductory biology students and analyzed the data from three assessments given to the students throughout the course. The aims were to determine whether there were any misunderstandings of aspects of the scientific method and whether there were any changes in their understanding throughout the course with various assessment types.

Assessments were also analyzed to determine their effectiveness in assessing the HOCS required in scientific inquiry.

Methods

Student performance in the scientific method section in a first year introductory biology course (BIOL 101) in the School of Life Sciences at the University of KwaZulu-Natal, Pietermaritzburg campus was investigated to determine students' misconceptions in aspects of the scientific method. Discipline-based science research was carried out using formative and summative assessments completed by first-year biology students at specific times throughout the course to firstly determine misunderstandings students had of various aspects of the scientific method and secondly whether these changed during the duration of the course or with differences in assessment types.

Of the students enrolled in the one-semester introductory biology course, 416 students completed all three assessments. The students registered for the course comprise of Black (>90%), White (<5%) and Indian students (<5%). This would suggest that by far the majority of students would presumably be English second language students. BIOL 101 is a pre-requisite course required for most degrees in the Life Sciences at UKZN. The introductory scientific method section of this course comprised two lectures, one tutorial and two practical sessions.

The first formative assessment was given to the students on the 28th February 2012. This assessment was in the form of a multiple choice test written at the completion of the scientific method section of the course. The second assessment, which included the scientific method, was a practical test conducted in April 2012. The scientific method question followed a similar format to the multiple choice test in February but required students to answer in short question format and included other testing of skills such as graphing. The final summative theory examination, written at the completion of the introductory BIOL 101 course in June 2012, also contained a section on the scientific method. The questions asked in this section were also in the format of short question answers. In all three assessments information was given about an investigation accompanied by a table of results (See Appendices 1, 2, 3).

Questions were identified that were consistent between all three assessments. These questions focused on the identification of the hypothesis / null hypothesis and identification of variables. Performance in these questions was compared across all three assessments. Questions were also examined to determine how specific questions in each of the assessments are structured and to determine what type of thinking these questions were eliciting in students. Questions were analysed using the Blooming Biology Tool based on Bloom's taxonomy of cognitive skills (Crowe et al., 2008).

Data analyses

Student performances on individual questions were analyzed using Repeated Measures Analysis of Variance (RMANOVA, Statsoft) with post-hoc Tukey tests to determine whether there was any significant improvement in students understanding of 1) hypothesis identification and 2) dependent or independent variable identification. All analyses were conducted using STATISTICA Version 7 (Statsoft, Tulsa, Oklahoma).

Grades are important in indicating whether students have given the correct or incorrect answer for a particular question. Quantitative analysis in this study identified whether students correctly answered the questions or not. However, it does not identify what the misconceptions are. In this particular study a qualitative analysis of students' answers was performed whereby students' answers were coded according to specific conceptions students gave. The number of individuals answering within each coded category was counted and then calculated as a percentage. These quantitative analyses were represented graphically showing the percentage of individuals in each coded category across all three assessments.

Bloom's Taxonomy coded questions

Using the Blooming Biology Tool (BBT) we categorized each question in each assessment into the six different cognitive levels (Crowe et al., 2008). The total marks allocated for each cognitive level were calculated for each assessment and then expressed as a percentage for comparison purposes.

Results

Comparison between percentages in three assessments

A comparison of the overall mean percentage and standard error achieved by BIOL 101 students in 2013 for the scientific method section across all three assessments showed that students performed on average better in the multiple-choice test (77.4 ± 1.11%, Mean ± SE) compared with the short question answers of the practical test (59.5 ± 0.71%) and the theory examination (65.5 ± 0.88%).

Hypothesis identification, quantitative results

There was a significant overall difference in students' performance in identifying hypotheses across the three assessments (RMANOVA: $F = 699.60$, $df = 2$ and 806, $P < 0.001$) (Fig. 1). However, *Post-hoc* tests revealed that students did not improve their results as expected.

Students performed significantly better in the multiple-choice tests (Tukey's HSD, $P < 0.001$) compared with the short answer question of the practical test. There was, however, a significant improvement in students' ability to identify hypotheses in the theory examination compared with the practical test (Tukey's HSD, $P < 0.001$). Both the multiple-choice question and the practical test required students to identify the hypothesis whilst the theory examination required students to identify the null hypothesis.

Hypothesis identification, qualitative results

A detailed qualitative analysis of the students' responses showed that 88.2% of the students correctly identified the hypothesis in the multiple choice test, from a selection of choices given (Fig. 2). Unfortunately, none of the distractors provided in this multiple-choice question included a prediction and therefore students' confusion of hypothesis with prediction was not tested. The detailed qualitative analysis of the practical test did however show that a large proportion of students (60.9%) mixed hypotheses with predictions whilst 2.4% identified the hypothesis correctly and 14.5% identified the hypothesis but left out vital information when formulating their hypothesis (Fig. 2). No students incorrectly identified null hypothesis in place of the hypothesis in the practical test.

By the end of the course (in the theory examination) over 80% of the students were able to identify the null hypothesis while only 29.7% had left out some information in the formulation of their null hypothesis (Fig. 2). Less than 10% of the students incorrectly identified predictions in place of the null hypothesis (Fig. 2).

Dependent and independent variable identification, quantitative results

Overall, students' performance in identifying dependent and independent variables correctly improved over the course of the study (RMANOVA: F = 32.55, df = 2 and 806, P < 0.001) (Fig. 3). Post-hoc tests revealed that students significantly improved their ability to identify variables by the end of the course (Tukey's HSD P < 0.001). However, students did perform worse in the short question practical test compared with the multiple-choice test (Tukey's HSD P < 0.001).

Dependent and independent variable identification, qualitative results

Although just over 50% of the students were able to correctly identify both the dependent and independent variables at the beginning of the course some of the students had a problem identifying the independent variable (26.3%) (Fig. 4). Less than 10% of the students confused dependent and independent variables in the multiple-choice test given as the first formative assessment of the course.

Interestingly, over 54% of the students in the practical test were unable to identify the dependent variables and often confused these with control variables (Fig. 4). Just over a third of the students were able to correctly identify both the dependent and independent variables. By the summative theory examination however, 73.6% of the students were able to correctly identify dependent and independent variables.

Mean percentage mark achieved in the three assessments

For the hypothesis question, students performed best in the multiple-choice test, dropping dramatically in the practical test and then showing improvement in the average mark achieved in the theory examination (Table. 1). The dependent and independent variables question shows a similar trend in higher mean percentages in the multiple-choice test compared with the practical test but showed an improved mean percentage in the theory examination (Table 1).

Bloom's Taxonomy analysis

When analyzing the individual questions of each assessment using the BBT it was found that 80.0% of the questions tested LOCS for the multiple-choice test and 20.0% were testing HOCS (Fig. 5). In the practical test 23.3% of the marks were allocated to the lower-order cognitive skills and 76.7% to the HOCS with much of the questioning focusing on the analysis skills. The theory examination however, tested more evenly across the lower-order and higher-order cognitive skills. The skill of application however, was not tested in any of the assessments.

Although there were no questions related to knowledge (Fig. 5) it must be noted that comprehension, application, analysis, synthesis and evaluation type questions all require knowledge that a student constructs (Bissel & Lemons, 2006). Questions considered to be knowledge questions refer to questions that test the recall of memorized facts. This LOS was not questioned in any of the assessments. Rather the comprehension of these facts was tested.

Discussion

As mentioned the call to change undergraduate biology education requires the rethinking and redesigning of curricula and courses (AAAS, 2010). Although many faculty staff identify that assessment data is important, research has shown that less than half use it regularly and yet research-based analyses of assessments can provide evidence to help guide decisions about a course (Elbert-May et al., 2003).

The purpose of data collection is to answer questions. We need to know what students know and why they do or do not know what we are trying to teach them. The significance of the evidence collected from assessments depends largely on the way in which assessments are structured and designed. The data produced from these assessments should provide valuable evidence to help identify misconceptions and misunderstanding and guide remedial strategies in course development (Pelaez et al., 2005).

What are our assessments telling us?

Quantitative analyses of grades can be a very useful tool in determining what students 'do' or 'do not know'. However, in order to determine why students 'don't know' one needs to go beyond simply analyzing grades (Elbert-May et al., 2003). In this study we analyzed the results of the introductory scientific method section across a number of assessments used throughout the BIOL 101 course. These ranged in the type of assessment tools used as well as the different cognitive skills assessed.

Focusing solely on the overall performance of students in this section revealed that students attained on average 65% in their summative examination for this section. However, they achieved much better results when doing a multiple-choice test in the beginning of the course based on similar criteria. This questions whether this difference was due to students' ability to answer different assessment tools better or whether there was a difference in the level of cognitive skills required between assessments. This highlighted the enormous responsibility placed on assessment design especially if it is to be used formatively and in the reform of courses and curricula.

Hypothesis identification

The level of cognitive skills assessed in the hypothesis identification question was consistent across all three assessments and allowed us to observe students' improvement in this throughout the course. Quantitative analyses revealed that students performed significantly better in the first test (multiple-choice) and poorest in the practical test but improved significantly in the final summative examination in this question. Both the multiple-choice test and the practical test asked the students to identify the hypothesis whereas the summative examination required students to identify the null hypothesis. Qualitative analyses revealed that over 88% of the students were able to correctly identify the hypothesis from a number of choices provided in the multiple-choice question but when asked to formulate their own hypothesis in the practical test only 16.9% were able to identify the hypothesis correctly, with over 60% of the students confusing hypotheses with predictions. Unfortunately, the multiple-choice question did not contain a prediction as a distractor to reveal whether students had this misconception prior to the practical test. The summative final examination assessment, although framing the hypothesis identification as a null, revealed that over 80% of the students were able to identify the null hypothesis correctly with less than 10% confusing prediction and null hypothesis. Our assessment analysis has revealed that the majority of students by the end of the semester long course are able to identify and formulate a hypothesis or null hypothesis from information given in a novel investigation.

Variable identification

The first assessment of the course revealed that just over 50% of the students were able to correctly identify both the dependent and independent variables. However, some of the students had difficulty identifying the independent variable. This is consistent with results obtained from other studies on variable identification (D'Costa & Sclueter, 2013).

The practical test revealed that students often confused dependent and independent variables with control variables. By the end of the course over 73% of the students were able to correctly identify dependent and independent variables.

Achieving our objectives?

Superficially one might conclude from these results that students have improved their ability to answer the questions in the scientific method section across the period of the course and that the course therefore has successfully achieved student learning. However, a conclusion can only be based on whether the course objectives have been achieved. This involves not only analyzing student performance but equally whether assessments have been adequately designed and structured to assess the objectives of the course.

It is useful to critically assess whether course objectives, instruction and assessment within our biology courses reflect the challenges proposed by the '*Vision and Change'* document. The main aim provided for BIOL 101, as laid out in the course handbook, is "to develop basic knowledge of structure and function" (Downs, 2012). It goes on to speak about the philosophy of the module where students will learn practical skills, thinking skills, conceptual understanding, reflection and writing skills. Although these include critical cognitive skills it is not clear where and how these are achieved. This philosophy is a broad overview of the entire module which covers content knowledge of scientific method, origin and evolution of life, cellular chemistry, DNA replication, transcription and translation, cell structure and function and introductory genetics. The competencies for each section are not specifically provided.

Evidence of both effectiveness of instruction and learning require some sort of reference or standard against which to test. Course objectives need to be made clear for both faculty staff prior to instruction and assessment, as well as for students (Crowe et al., 2008).

Are we assessing scientific skills in our scientific method questions?

Scientific inquiry has been acknowledged by AAAS as an essential aspect of science teaching, learning and assessment (AAAS, 2010). Implementation into the undergraduate degree is more challenging than the acknowledgement of it. The question one needs to ask is what constitutes scientific teaching and assessment? How must courses be structured and assessments designed to adequately develop and assess future scientists?

For this to be achieved, the '*Vision and Change'* document proposes the development of competencies which require the development and assessment of critical cognitive skills (AAAS, 2010). Often the ways in which assessments are formulated reflect the manner in which instruction occurs. Students will not develop their ability to think at higher cognitive levels if they are only required to regurgitate large amounts of facts (Lemons & Lemons, 2013).

Most faculty staff grapple with formulating assessments that adequately assess critical thinking skills (Lemons & Lemons, 2013). Crowe et al.'s (2008) Blooming Biology Tool can provide a tool against which they can critically test whether they are assessing HOCS in their courses. In analysing the three assessments it was noticed that a high percentage of the questions asked in the scientific method question were testing LOCS rather than HOCS. One would expect that the scientific method section be predominantly HOCS but often the way in which the questions are asked deludes one into thinking HOCS are being tested when, in fact, they are not.

An analysis of the three assessments revealed that 80% of the multiple-choice test consisted of comprehension-type questions testing LOCS. This would probably account for the high marks achieved by students in the multiple-choice section. The students performed poorest in the practical test. On analysis of the question types using the BBT it was found that only 23.3% of the questions were considered to be testing LOCS and 76.7% tested for HOCS. The students seemed to improve their performance in the scientific method section during the theory examination. However, this may have been due to the higher percentage of marks allocated to LOCS (50%) questions compared with to the practical test.

Using the BBT, a taxonomy of cognitive skills that has been previously used in undergraduate biology (Crowe et al., 2008), our basic analysis has revealed that even scientific method type questions may in fact not be testing critical thinking and careful and purposeful consideration needs to occur when designing assessments. However, it has been found that biologists have different views on whether HOCS are being tested or not (Lemons & Lemons, 2013). Indeed, with about 35 taxonomies of cognitive demand, there appears to be little agreement as to what approaches effectively test HOCS.

Two questions were analysed in this study that were analogous across all three assessments, namely hypothesis identification and dependent and independent variable identification. Most of the questions required students to extract information in order to answer questions, a comprehension skill which requires LOCS. The identification of variables questions in all three assessments were considered to be testing comprehension (a LOCS) as students were only required to identify the variable from a comprehension-type text.

Analysis of cognitive skills required to answer the hypothesis question across all three assessments revealed that this question type could be considered a synthesis question (HOCS).

However, it is argued that one can't really test synthesis skills in a multiple-choice question since students are really making a choice between possible answers rather than synthesizing a unique response (Crowe et al., 2008). This possibly could be the reason for students performing better in the multiple-choice test for this question compared with the other two assessments which required students to use information to formulate or 'synthesize' their own hypothesis. However, one could argue that students did need to identify information from a text and synthesize this information in order to make a correct choice. Distractors would play an important role in testing the students' ability to synthesize in a multiple-choice type question. If the distractors are too obviously incorrect then recognition of the correct answer may not elicit the use of synthesis skills. The formulation of a hypothesis may not be considered a higher-order cognitive skill if students merely extract the dependent and independent variables from a text and formulate the hypothesis using a learnt procedure (Crowe et al., 2008). Higher-order cognitive skills are tested when students are required to create something new. In other words, HOCS are required when students formulate new hypotheses and design experiments without the use of information provided.

One of the factors highlighted by biologists in determining whether HOCS have been tested or not, is linked with student experience (Lemons & Lemons, 2013). Although each of the scientific method questions used contained an unseen experimental scenario the structure of the question was analogous across all three assessments. Each question required students to extract information set out in a comprehension-type format with results provided. Students were then asked to identify variables and provide the hypothesis of the experiment. This type of questioning was also provided in tutorials during class time as examples for students. One could argue that this type of questioning could instil a type of 'rote-learning' of a process rather than critical thinking. Thus, the questions aimed to test HOCS are in fact testing LOCS due to the 'familiarity' through student experience.

Preparation of students for assessment in scientific method?

Anderson & Rogan (2011) argue that in the designing of courses and curricula, it is important that instruction and assessment be delivered at the appropriate intellectual level or standard for the educational year. The results attained in these three assessments have indicated that students had difficulty in identifying variables and formulating hypotheses and null hypotheses when information was provided.

Higher-order cognitive skills are built on lower-order cognitive skills of knowledge and comprehension of content (Bissel & Lemons, 2006). The testing of HOCS assumes that students have acquired the foundational scaffolding developed from lower-order thinking. It is necessary that through instruction and formative assessments that students gain knowledge and understanding associated with LOCS before the development of HOCS.

Although scientific inquiry: observation, hypothesis formulation and designing of experiments are taught in the biology curriculum in schools (Department of Education, 2003), students can register for BIOL 101 without any previous training in biology (Downs, 2012). Not only does this introductory biology course have to consider students from a variety of different socioeconomic, but also different academic backgrounds. Course objectives and competencies are likely to differ at universities which are comprised predominantly of English-second language learners, who may or may not have any formal biological background, compared to more westernized universities. The objectives and competencies of BIOL 101 to a large extent would be governed by prior knowledge and skills of students entering the course. The aim for

BIOL 101 would thus be to ensure that all students entering second year level have acquired the same level of competence in scientific inquiry.

Biology is wrought with technical jargon foreign both to the English-second language student as well as to students entering the field for the first time. Students have to learn a scientific language where ordinary words are used with non-vernacular meanings, there is often the omission of words in sentences, complex sentences containing biological terms and abstract nouns and the use of the passive voice (Fang, 2006).

It has been suggested that to assist students with these challenges, instruction should address decoding technical terms, building schema around scientific concepts, rephrasing scientific texts in their own words and training them to be aware of the 'signposts' to allow students to understand linkages among ideas (Turkan & Liu, 2012). The continued use in BIOL 101 of analogous questions in containing a comprehension-type text may not be testing critical thinking skills but may rather enforce an understanding of what a hypothesis is and how to formulate it as well as identify the variables involved in an investigation. Indeed, Grunwald & Hartman (2012) maintain that "in order for students to master any of these experimental skills, they must be able to identify the numerous system variables that can affect an experiment and to understand the impact that these variables have on the experimental results (pg 29)".

One caution in the design of these scientific method questions used in BIOL 101 assessments is the accuracy in which these questions portray the scientific process. The hypothetico-deductive method requires hypothesis formulation prior to the design and collection of experimental data. The manner in which the scientific method question is designed requires students to formulate hypotheses based on the results given. It is crucial that this type of questioning does not instil misunderstandings that hypotheses can be formulated post data collection. This omits entirely the cognitive aspect of scientific inquiry and detrimentally affects any inferences produced through the investigation.

Conclusion

The '*Vision and Chang*e' document requires change in how we approach undergraduate teaching and assessment to ensure undergraduate biology education for ALL students (AAAS, 2010). It recommends that the scientific process be introduced to students early into all undergraduate biology courses. An introduction to the scientific inquiry has indeed been achieved through the scientific method section of BIOL 101. The '*Vision and Change'* document is however, not clear to what extent cognitive skills should be developed at the introductory level courses (AAAS, 2010). Perhaps what has been achieved in BIOL101 is sufficient to provide a foundation to develop HOCS in the latter years of undergraduate biology courses.

Annual reform in courses must centre on the objectives and competencies to be developed. Instruction and assessments require clear and detailed objectives in order to be effective in guiding future teaching. Meaningful inferences will only occur if assessments accurately reflect the instruction that has occurred in the classroom environment. Assessments play an essential role in determining misconceptions and misunderstandings provided that these assessments are carefully structured and designed. Prior to the designing of assessments one needs to determine the purpose of the assessments. Many factors play a significant role in testing: these include the content and concepts to be covered as well as the cognitive skills to be assessed. The manners in which assessments are structured have also shown to play a role in whether students are in fact being assessed for HOCS or LOCS. Our assessments need to be critically analysed to determine whether they are in fact assessing what they originally were purposed to achieve. What are our assessments telling us? The answer to this question relies predominantly on the original purpose of the assessment and how they have been strategically designed to elicit meaningful results to help guide biology introductory courses in the future.

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Table 1: Results for hypothesis question and dependent and independent variable identification across three assessments (multiple-choice test, practical test and theory examination) in a first year biology undergraduate course in KwaZulu-Natal, South Africa (n=416).

	Average percentage mark attained for the hypothesis identification question	**Average percentage mark attained for the dependent and independent variable identification question**
Multiple-choice test	92.5 ± 1.07	68.3 ± 1.81
Practical test	26.9 ± 1.4	59.5 ± 1.73
Theory examination	77.4 ± 1.68	78.8 ± 1.86

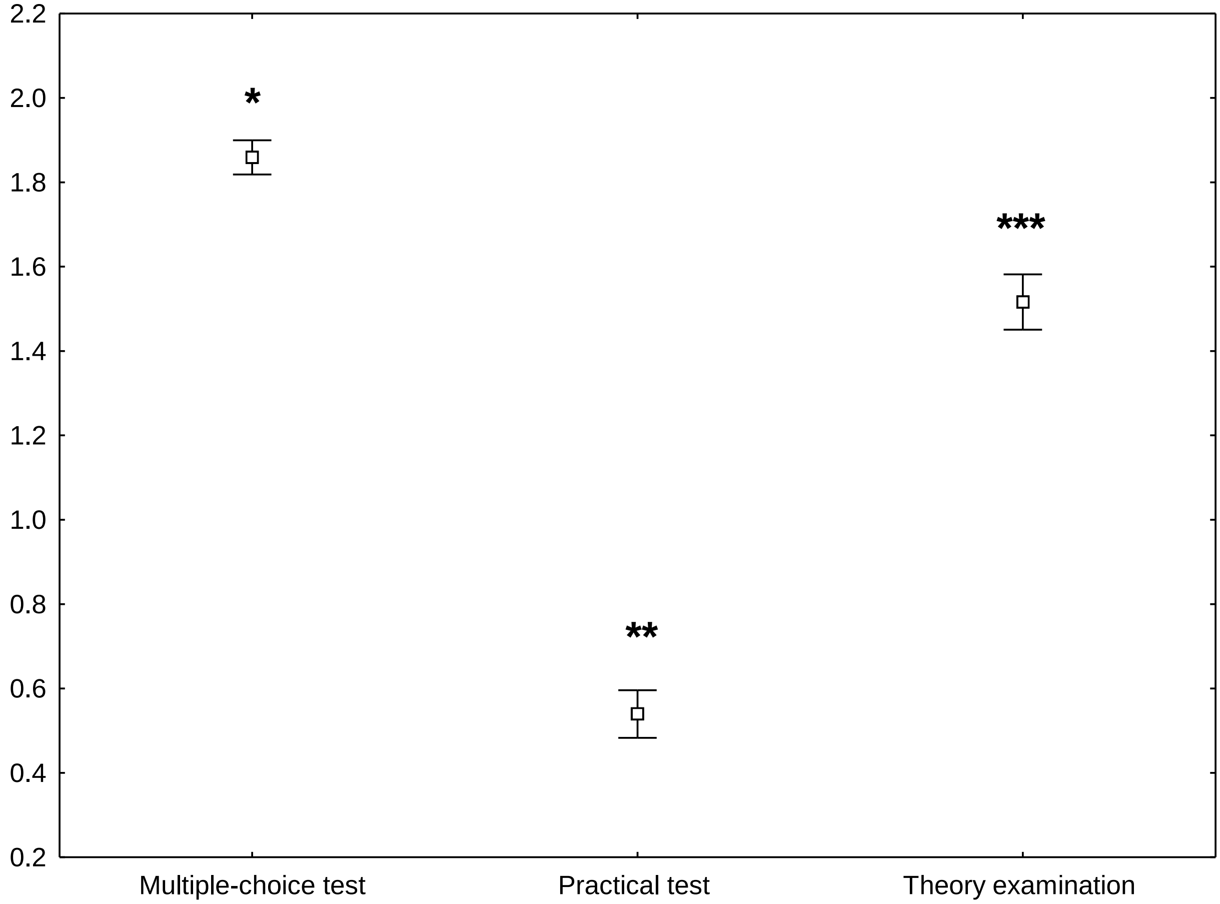

Figure 1: A comparison of biology undergraduate students' marks between three assessments (multiple-choice test, practical test and theory examination) for a hypothesis identification-type question. Stars (*) indicate where significant differences lie (n=416).

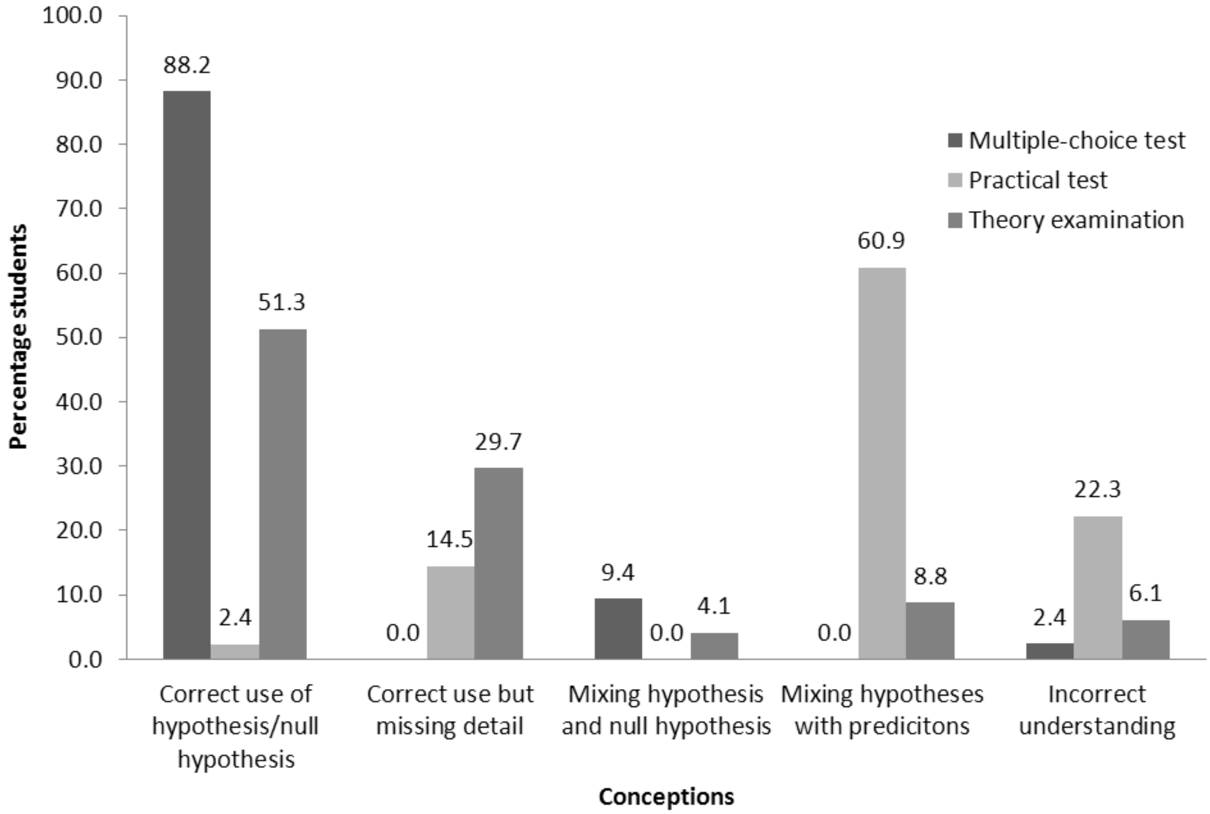

Figure 2: Percentage of undergraduate biology students categorized into conceptions in response to hypothesis questions in three assessments (multiple-choice test, practical test and theory examination) (n=416).

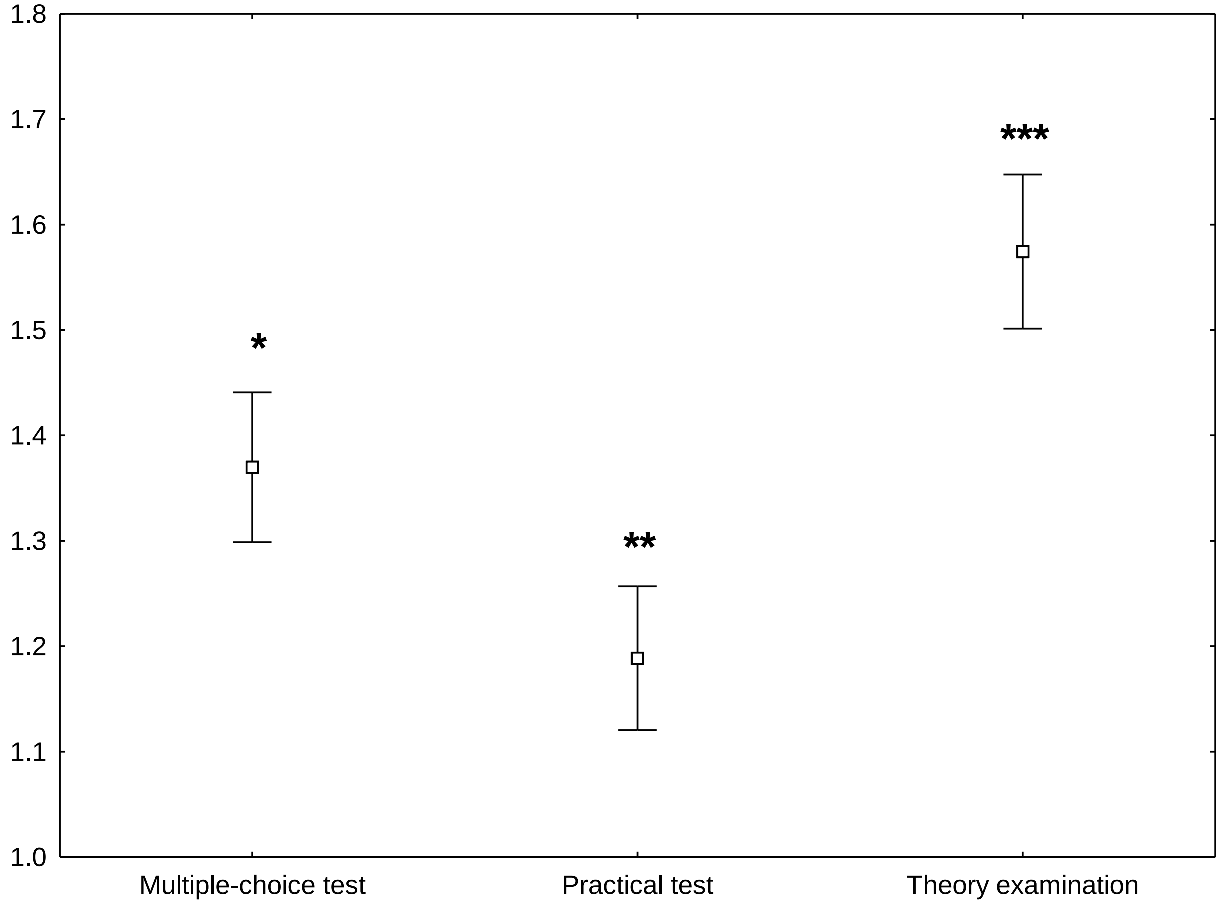

Figure 3: A comparison of undergraduate biology students' marks between three assessments (multiple-choice test, practical test and theory examination) in the identification of dependent and independent variables. Stars (*) indicate where significant differences lie (n=416).

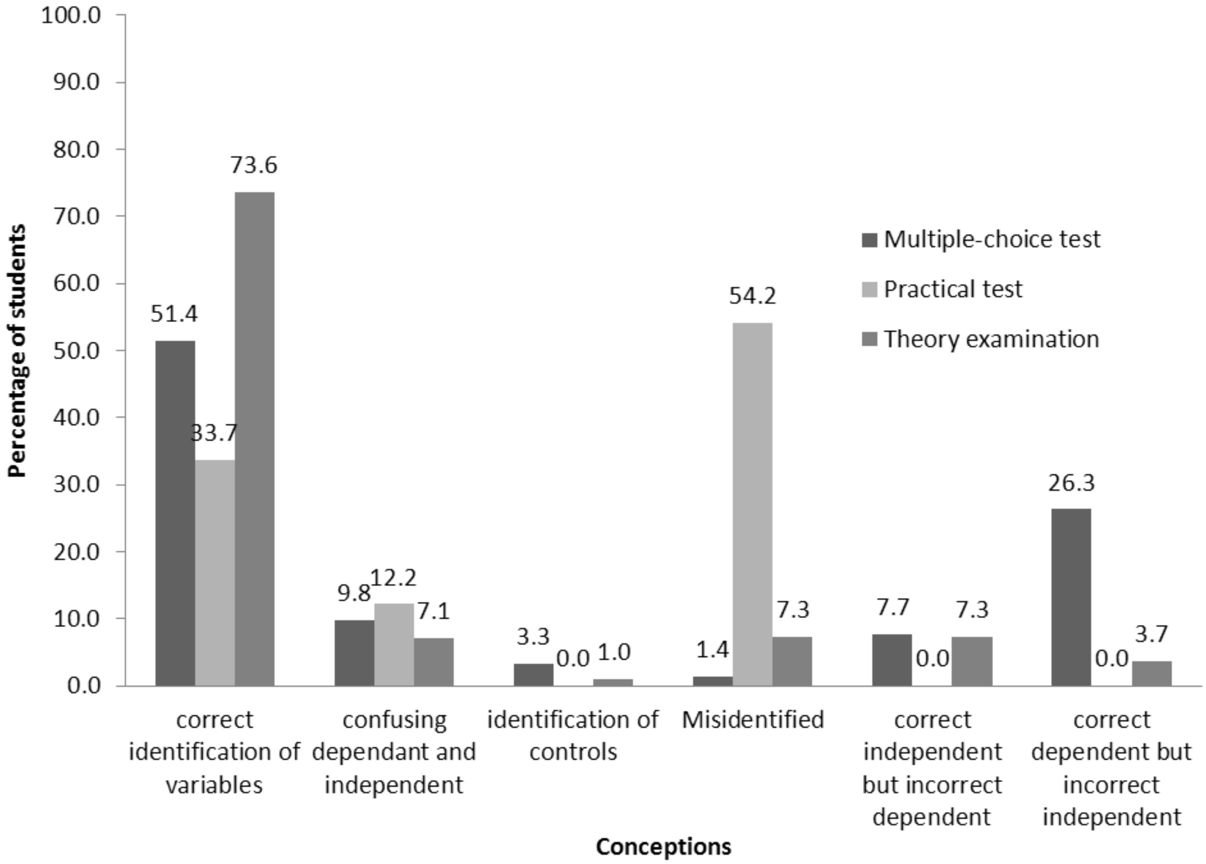

Figure 4: Percentage of undergraduate biology students' conceptions in response to identification of dependent and independent variable questions in three assessments (multiple-choice test, practical test and theory examination) (n=416).

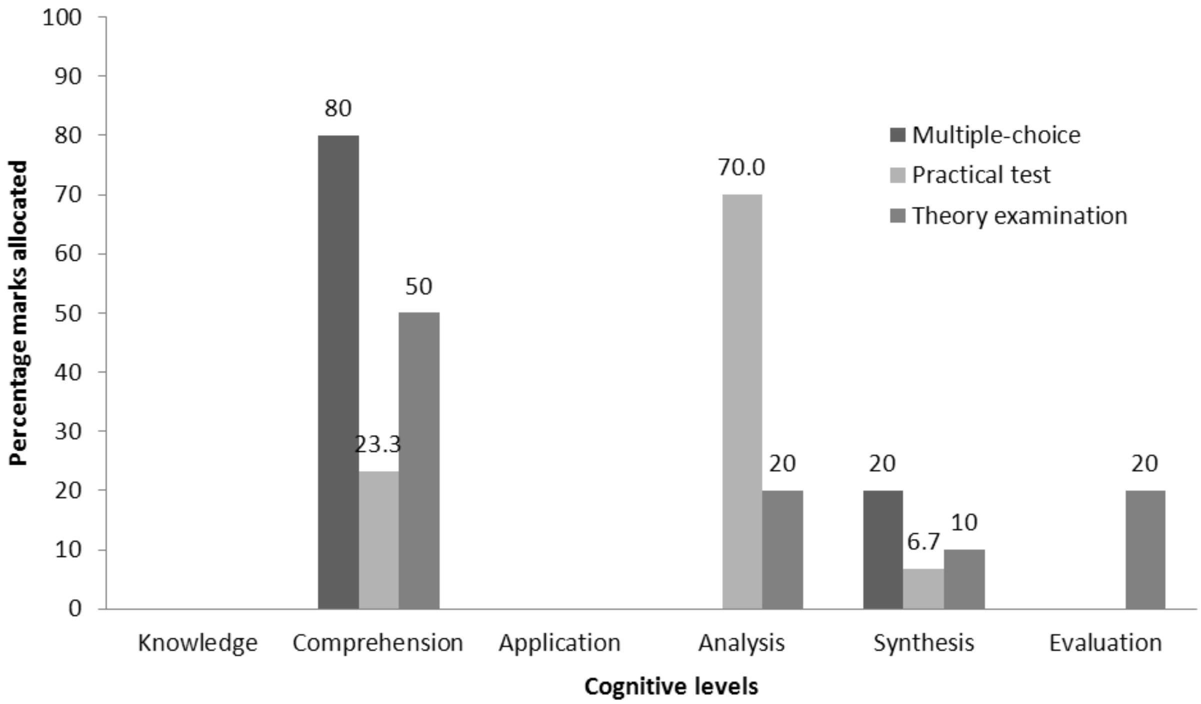

Figure 5: Percentage of marks allocated to different cognitive levels (according to Crown et al.'s BBT 2008) in the scientific method question of three assessments (multiple-choice test, practical test and theory examination) (n=416).

Appendix 1: Formative test questions

Section A: Multiple Choice Questions (20 marks)

A biologist is interested in studying the effect of growth-enhancing nutrients on the growth of a marine fish *Sardina pilchardus* or pilchards. The biologist ordered young pilchards of the same age from a supply house for use in the study. The experiment was conducted in a laboratory where 10 pilchards were placed randomly into each of 12 similar tanks with the same sea water in a controlled environment (temperature was 25°C and salinity of water was kept constant). The biologist used 3 different growth-enhancing nutrients (A. B. and C) that were given as 100g daily to four respective tanks. The biologist monitored the increase in body mass and length each week on a Friday for 6 weeks. Some of the results are presented in Table 1.

Table 1. Mean (+ SD) body length as an indicator of growth rate of *Sardina pilchardus* using 3 different growth-enhancing nutrients (A. B. and C)

	A	B	C
Initial length (mm)	15.5 ± 3.2	15.6 ± 3.4	15.4 ± 3.6
Final length (mm)	100.5 ± 12.6	125.2 ± 5.5	137.3 ± 4.0

1. What would have been the hypothesis for this experiment?

   a. Growth-enhancing nutrients do not affect the growth of pilchards.
   b. Salinity affects the growth of pilchards.
   c. Growth-enhancing nutrients affect the growth of pilchards.
   d. The final length of pilchards is greater than their initial length.
   e. Time of year affects growth rate.

2. What is/are the independent variables?

a. Whether or not pilchards receive growth-enhancing nutrients A, B or C.

b. Frequency of feeding.

c. Number of pilchards present.

d. Total growth of pilchards.

e. Type of fish used.

3. What is the dependent variable?

a. Whether or not pilchards receive growth-enhancing nutrients A, B or C.

b. Frequency of feeding.

c. Number of pilchards present.

d. Total growth of pilchards.

e. Type of fish used.

4. Which were the control variables in the experiment?

a. Amount of growth-enhancing nutrients given daily

b. Number of pilchards present in each of the four tanks receiving the respective growth-enhancing nutrients

c. Six weeks

d. 10 *Sardina pilchardus* in each tank.

e. All of the above.

5. Why were four tanks with ten pilchards in each used for each treatment?

a. To show the results were not by chance.

b. To avoid confounding effects.

c. For replication.

d. To avoid sampling error.

e. All of the above.

Appendix 2: Practical questions

Question 1 (30 marks)

A company is experimenting with growing lettuce using hydroponic technology. Hydroponic technology involves growing plants in containers of growth solution in a greenhouse. No soil is used. The growth solution that the company uses contains water, nitrogen, and phosphorus. The company wants to know if adding iron to this formula will improve lettuce growth. Lettuce seedlings are grown using three treatments with 100 seedlings in each: Treatment 1 standard water, nitrogen, and phosphorus; Treatment 2 standard water, nitrogen, and phosphorus plus 0.5g iron; and Treatment 3 standard water, nitrogen, and phosphorus plus 1.0g iron. The seedlings are grown in the same greenhouse with the temperature set at 25^{o}C. Seedlings were monitored for three weeks and their masses measured weekly as an indication of growth.

Table 1. Weekly mean $\pm$ standard deviation mass of lettuce grown using the three respective treatments.

Week	Treatment 1 (g) (n = 100)	Treatment 2 (g) (n = 100)	Treatment 3 (g) (n = 100)
1	10.1 $\pm$ 0.2	11.2 $\pm$ 0.3	12.4 $\pm$ 0.1
2	15.0 $\pm$ 0.5	16.1 $\pm$ 0.4	17.2 $\pm$ 0.5
3	20.5 $\pm$ 0.2	21.3 $\pm$ 0.2	22.3 $\pm$ 0.2

a. Give a hypothesis for this experiment. (2)

b. List the controlled variables in this experiment. (5)

c. What was the dependent variable? (2)

d. Present the results as a Figure with a legend using the graph paper provided. (10)

e. Explain the results obtained in terms of your hypothesis. (5)

f. Was there a control group? Explain. (2)

g. Were there any confounding variables? (2)

h. What would be the company’s recommendation for growing lettuce following the experiment? (2)

Appendix 3: Summative exam question

Question 1

In an experiment to determine the effect of ambient temperature on metabolic rate (measured as oxygen consumption) of Cape Parrots *Poicephalus robustus*, ten adult birds were kept singly in outside cages (1 X1 X 3m) during the summer. They were fed and watered daily. After being weighed, five individuals were placed in plastic containers in a temperature cabinet set at the particular experimental temperature at 16h00. Air was drawn through and the amount of oxygen consumed by each bird determined every 5 min so mean hourly rates of oxygen consumption for each bird were determined through the night. The lowest hourly value was taken as the resting oxygen consumption for a particular bird. Birds were weighed and returned to their cages at 07h05. The next evening the other 5 birds were tested in the same way. Birds were measured at 5, 10, 15, 20, 25, and 30^{o}C.

Table 1. Change in rate of consumption of Cape Parrots with temperature (n = 10).

Temperature (^{o}C)	Mean resting oxygen consumption (ml O_2 g^{-1} h-^{1})
5	3.5
10	3.1
15	2.6
20	2.3
25	1.5
30	1.0

a. What is the null hypothesis for this experiment? (1)

b. What are the dependent and independent variables? (2)

c. What are the possible confounding variables in this experiment? (3)

d. Would you accept your hypothesis? Why? (2)

e. Has sufficient attention been paid to replication and randomization? Why? (2)

CHAPTER 5

A Case Study Assessing Third Year Biology Students Understanding of Scientific Inquiry Concepts

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Abstract

The purpose of this case study was to determine the types of conceptions that third year biology students hold regarding hypotheses, predictions, theories and aspects of experimental design. These conceptions of students were compared across two geographically separated campuses of the University of KwaZulu-Natal, namely the Pietermaritzburg (n = 28) and Westville (n = 50) campuses. They were also compared to descriptions located in prescribed textbooks and course manuals throughout their undergraduate biological studies.

The results indicate that there is variability between and across campuses in students' descriptions of research hypotheses, predictions and theories, repetition and randomization. These conceptions were sometimes partial conceptions while in other instances they were completely incorrect. Interestingly, many of the students' responses lacked essential elements which could be found in the prescribed textbook and course manuals. The variability in student

responses across campuses could be a result of differences in faculty instruction and therefore more research is required to test this. These results also indicate the necessity for courses to be designed with more consistency in concepts to be developed.

Keywords: *Conceptions, research hypotheses, null and statistical hypotheses, predictions, theories*

Introduction

Scientifically literate undergraduates have been the primary goal of many curriculum reform documents over the past few decades (American Association for the Advancement of Science [AAAS], 1990, 1993; National Research Council [NRC], 1996, AAAS, 2010; Achieve, Inc., 2013). Scientific literacy is broadly described as the ability to make informed decisions on science, technological and societal issues and is fundamentally connected with innate understandings of scientific concepts, the processes of scientific inquiry and the nature of science (Bell *et al*., 2003).

Teaching science that yields undergraduates who are proficient in science requires first and foremost the identification of student conceptions (Barnett and Morran, 2002). Diagnosis of students' preconceptions, alternative conceptions and misconceptions are necessary in order for teacher-facilitated conceptual change to take place (Grayson *et al*., 2001; Morrison and Lederman, 2003). The term misconception denotes any ideas that are held by an individual that are not consistent or in conflict with those generally accepted by scientists (Yip, 1998). These misconceptions can result from an individuals' prior experiences, alternative belief systems, and confusion between the scientific meaning and the common meaning of a specific term (Michael *et al*., 1999). Misconceptions that appear to be prevalent in science are often difficult to amend due to either their inconsistency in current scientific knowledge or the abstract nature of these conceptions (Wandersee *et al*., 1994). If, however these concept difficulties and/or alternative conceptions are not confronted, students resort to rote memorization of isolated pieces of science and executing meaningless inquiry (Hestenes *et al*., 1992).

Misconceptions in science have also been associated with the way teachers and textbooks present information (Seymour and Longden, 1991; Yip, 1998). Misconceptions may also be generated through an individual's life experiences prior to former instruction, which include informal ideas formed from everyday experiences. Conceptual difficulties may arise when having to discriminate scientific concepts that carry similar terminology to everyday language (Fang, 2006). However, it is thought that those concepts that are generally considered more complex and abstract are not necessarily 'naïve' concepts developed on their own through life experiences but rather are likely to have formed as a result of incomplete or improper views developed in a more formal setting (Yip, 1998). They are in other words linked to ineffective learning (when prerequisite knowledge is absent in the construction of a new concept) or through poor instruction (excessive emphasis on the acquisition of factual information rather than development of critical thinking). It is essential for instructors to establish whether students have mastered prerequisite concepts before continuing in the instruction of more complex ones (D'Costa and Schlueter, 2013). Sometimes a source of misconceptions are the instructors themselves who are less competent in specific subject matter and convey incomplete or erroneous views through inaccurate instruction or uncritical use of textbooks (Sanders, 1993). Even scientists are not immune to the misapplication and misuse of various scientific concepts and display inconsistency in the applications of some definitions of terms (Kugler, 2002; Hiebert, 2007; Hutto, 2012).

Textbooks contain the context, definitions and explanations for specific concepts in a discipline (Hartley *et al*., 2012). Although textbooks play an important role in the provision of fundamental knowledge they often provide a simplified picture of science with the aim of ensuring that they are comprehensible to students. Conceptions depicted in this way may perpetuate misunderstandings either because of inaccuracy in representing specific concepts or through a lack of elaboration of the interrelationships between concepts both within and between disciplines (Yip, 1998; Hartley *et al*., 2012, Parker *et al*., 2012). The simple and concise nature of textbook definitions also encourage rote memorization rather than critical thinking (Hartley *et al.*, 2012). When undergraduates learn concepts as entities detached from their practical application, they fail to grasp the essential mechanisms involved in the development of scientific knowledge (Bautista *et al*., 2013). The way in which instructors represent concepts of science is often related to how concepts are presented in preferred textbooks or course manuals (Kugler, 2002). An examination by Kugler (2002) of 12 commonly used biology textbooks revealed multiple definitions and inconsistent labelling of concepts in and between textbooks. He identified inconsistency in the definition and application of hypotheses, theories, laws and principles. Scientific literacy requires the ability to integrate conceptions of the nature of science and scientific inquiry with subject matter.

Teaching science for conceptual change begins with eliciting students' preconceptions and misconceptions prior to the development of reform strategies for instruction (Barnett and Morran, 2002). This study aimed at revealing the types of conceptions held by third year undergraduate students to determine their conceptual understanding of hypotheses, predictions, theories, replication and randomization prior to conducting a mentored research project. These conceptions are also compared with textbook and third year course manual definitions. In chapter

4 we found significant cross-campus differences among undergraduate students in terms of their conceptions of aspects of the scientific method. In this current study we therefore assessed whether between campus differences would occur when teaching and instructional material were standardized. Effectively a difference between campuses would reflect instructors influence at a campus level.

Methods

Context of learning environment

The study took place in a relatively large, research university which exists over three campuses in southern Africa (University of KwaZulu-Natal). A merger that took place between the University of Natal and the University of Durban-Westville in 2004 meant that courses that were distinct in the original universities had to be merged and conducted across two campuses. The School of Life Sciences is located on the Pietermaritzburg and Westville campuses. Areas of specialization include biodiversity, evolutionary biology, animal and plant ecology, marine biology, microbiology, ecotoxicology, entomology, parasitology, biochemistry, genetics, biology, cellular biology, ecology, marine biology and systems biology.

The majority of Life Science courses in the undergraduate curriculum are primarily lecture-based with laboratory sessions offered to students as opportunities to learn techniques and verify concepts taught in class. In their third year students are offered the opportunity to do a biology course (BIOL 390) where they conduct mentor-mediated research projects. In these projects students are required to generate questions, hypotheses and predictions (if necessary), and to design, conduct and reason through a research investigation. The size of the groups differs across campuses with the Westville campus registering more students in the School of Life Sciences than the Pietermaritzburg group.

Data collection and analysis

An open-ended questionnaire was presented to third year Life Science students across campuses prior to them conducting their BIOL 390 projects (Appendix 1). The pre-project questionnaire was conducted to explore themes in students' conceptions of scientific inquiry to assess the depth and accuracy of students' conceptions. These were also compared across campuses to see if there were any differences between students' conceptions of 1) research hypotheses; 2) alternative hypotheses; 3) null hypotheses; 4) the role of theory; 5) repetition and sample size and 6) randomization.

The questionnaires were analysed qualitatively. Each student's questionnaire responses were inputted into an excel spreadsheet under the headings related to particular questions. Upon initial reading of questionnaires, specific terms emerged from the data in association with specific concepts. Specific terms that emerged were identified and entered into a column next to each student's response. These terms were clustered, reduced and refined through multiple cycles of data interpretation. The refined clustered terms were then tallied and represented as percentages. Differences between the Pietermaritzburg and Westville campus questionnaires were then reviewed.

Results

The results present emergent themes in participants' descriptions of research hypotheses, null hypotheses, alternative hypotheses, predictions, randomization, repetition, and the role of theory.

A difference in content knowledge was found between participants across campuses in many of these areas of scientific inquiry.

1. **Research hypothesis: What is a research hypothesis?**

Overall, it was found that participants' definitions of research hypotheses contained terms associated with descriptions, requirements, their formulation, and their purpose (Table 1). In other words, what they are, how they are developed and why are they used.

Both the Pietermaritzburg and Westville campus student groups expressed a variety of ideas regarding what a research hypothesis is. The term "statement" was the most frequently used term to describe the research hypothesis and was described in half the participant's answers from both Pietermaritzburg and Westville. A variety of other terms were used by the remainder of individuals which described it as a question, prediction, educated guess, an expected outcome or result. Only one individual (3.6%) from Pietermaritzburg and 3 participants (6%) from Westville explicitly stated that a research hypothesis was an explanation.

A theme that emerged from individual's descriptions indicated the requirement for research hypotheses to be both falsifiable and tested (Table 1). Whilst under 20% of the individuals from both Pietermaritzburg and Westville stated that research hypotheses should be falsifiable, about a quarter declared that they should be tested or testable. A larger proportion of the students from Westville (35%) included the testing of hypotheses via experiments in their definitions compared with students from the Pietermaritzburg campus (7.1%).

A quarter of the individuals from Pietermaritzburg and just over a fifth of individuals from Westville mentioned that research hypotheses are based on observations. In relation to their purpose, only 7.1% from Pietermaritzburg and 10% from Westville stated that research hypotheses made predictions. About 14% of students from Pietermaritzburg and 4% from Westville maintained that the research hypothesis is proved right or wrong or true or false. The concept that the research hypothesis is "supported" was only mentioned by 6% of the individuals of the Westville group and not at all by individuals in the Pietermaritzburg group.

"A research hypothesis is a scientific thought out explanation to a question asked after an observation has been made. This hypothesis is the basis of your research and all experiments will be based on this" (Westville).

2. Null hypothesis: What is a null hypothesis?

The greatest proportion of individuals from both the Pietermaritzburg (50%) and Westville campuses (48%) described the null hypothesis to be either a negative hypothesis or opposite of the alternative hypothesis. As mentioned of the research hypothesis, some individuals described the null hypothesis to be falsifiable (Pietermaritzburg: 21%; Westville: 10%) and testable (Pietermaritzburg: 21%; Westville: 38). A greater proportion of Westville group also included a reference to experiments in their definitions compared with the Pietermaritzburg group (Table 2). Interestingly, a marked difference was noted between the two groups whereby almost half the individuals at Westville described the null hypothesis as having a relationship of no difference whilst less than 15% of Pietermaritzburg group specified this in their definitions. Additionally, a greater proportion of the Westville group (18%) associated the null hypothesis with statistics whilst this association was only mentioned by one individual from the Pietermaritzburg campus.

3. Alternative hypothesis: What is an alternative hypothesis?

Although 29% and 36% of individuals from Pietermaritzburg and Westville campuses respectively described alternative hypotheses as statements, the greatest proportion of individuals focused on the fact that they were hypothesis that were the opposite to the null hypothesis and written in a positive form (Table 3). The requirement of alternative hypotheses to be falsified was stated by only 7% of the individuals from the Pietermaritzburg group and not at all by those from the Westville group. Less than a quarter of the individuals from both campuses mentioned that the alternative hypothesis must be tested or testable. Individuals, particularly from the Westville campus (30%), specifically mentioned that alternative hypotheses contain the words “there is a difference” or “has an effect on” in their composition. Once again few students mentioned an association with statistical analysis in any form or other (3.6% from Pietermaritzburg campus and 8% from Westville campus).

4. Predictions: What is your understanding of a prediction?

Once again a proportion of the students from both campuses use the term statement in their description (35.7% of Pietermaritzburg; 22% of Westville; Table 4). While about 10% from both campuses describe a prediction as a guess, the majority of the students both in Pietermaritzburg (82.1%) and in Westville (92%) described a prediction as what they think, expect or predict will happen or be the outcome of the research. Of these percentages of individuals 43% and 52% specifically associated this expectation to outcomes of experiments. Only 21% and 12% of individuals from Pietermaritzburg and Westville campuses respectively linked predictions to hypotheses in their definitions.

5. Theory: What role does theory play in research?

Results indicated that students’ conceptual understanding of the role theory plays in scientific research concentrates on three attributes: 1) it serves as background knowledge or information; 2) it is used to guide research providing a framework from which hypotheses can be formulated or used to guide experimental design and lastly; 3) it's role is to back up and bring understanding to experimental results (Table 5).

The majority of the students from both the Pietermaritzburg campus (57%) and the Westville campus (48%) consider the primary role of theory is to provide background information and previous knowledge of research (Table 5). The next highest proportion of students' responses from the Pietermaritzburg campus (35.7%) was characterized by a cluster of phrases that corresponded theory bringing explanation and understanding to the results. This was however, not revealed in the Westville campus. Aside from the 48% of responses which viewed the role of theory as providing background information or previous knowledge of research, the rest of the responses were fairly evenly spread (between 10 – 16%) over other ideas such as: it guides research, brings explanation and understanding, backs up or supports results, something to compare results to and supported by numerous testing.

Students' conceptions of the role of theory in scientific investigations is limited. Whilst only 2% of the Westville campus individuals view theory as necessary in scientific reasoning, this was not acknowledged at all by students from the Pietermaritzburg campus. Again none of the students from the Pietermaritzburg campus and only 12% from the Westville campus explicitly convey an understanding that there is a relationship between theory and the results obtained from investigations. This is further exemplified by the fact that very few students (less than 10%) from both campuses specifically state that theories are supported by numerous investigations.

6. Replication and sample size

A range of responses were exhibited from both campuses in response to the question regarding replication and sample size (Table 6). While the greatest proportion of responses that came from the Pietermaritzburg area were simply the fact that they must be large (32.1%), the highest proportion of students' responses from the Westville campus (18%) added that the sample size must be large in order to ensure the accuracy or reliability of results (Table 6). The differences in responses between Pietermaritzburg highlights the possibility that the Westville campus students have a better understanding of the purpose of sample size and its association with statistics, whereas the Pietermaritzburg students appear to not have made this connection.

Responses associated with replicates were very interesting. Almost a quarter of the students from the Westville campus explicitly stated that three replicates were the minimum number of replicates to be used in an investigation. The Pietermaritzburg campus responses displayed more variety in their responses to replicates. Whilst 14.3% also referred to a minimum of three a fair number also specifically included the fact that a minimum of ten is necessary to achieve suitable replication (Table 6). Whether these differences are associated with differences with the type of disciplines offered i.e. (more laboratory based or field ecology based disciplines) at each campus is something to be considered.

When asked why replication is necessary the majority of the students from Pietermaritzburg campus used terms associated with the reduction or elimination of bias (60.7%), whilst the majority of the Westville campus students related it to improving accuracy and reliability (56%) (Table 7). Other responses included ensuring that results were not due to chance or fluke, reduction of errors and the influence of confounding factors. Very few students from both campuses referred to statistics in their responses, whilst 21% from the

Pietermaritzburg campus and 18% from the Westville campus associated replication with experiments (Table 7).

7. Randomization in experimental design

In response to the question on randomization there seems to be a greater consistency in the responses between the Pietermaritzburg and Westville campuses, with the majority of responses associating randomization with the reduction or elimination of bias (Pietermaritzburg: 60.7%; Westville: 64%). Interestingly, this is the same percentage of students from the Pietermaritzburg campus that responded similarly to the question regarding sample size. It is unclear whether these students believe that sample size and randomization play similar roles. Other responses that were exposed were that randomization is believed to provide equal chances of being selected and provided a better representation of the population (Table 8). Some students also displayed confusion with regard to randomization. These included the process of randomization with the terms control and replication.

Prescribed textbook and course manual definitions

Although not the only source through which students gain science definitions, textbooks and course manuals do play an integral role in the development of science conceptions. Table 9 presents definitions extracted from two of the most commonly used textbooks selected for the Introductory Biology Course at the University of KwaZulu-Natal as well as definitions from a course manual provided to students registered in the BIOL 200 course in second year.

Interestingly, in contrast to the results obtained from student responses in the questionnaire regarding the defining of research hypotheses, all three of the provided texts include the use of explanation in their description of a research hypothesis (Table 9).

Synonymous with the majority of the students' responses is the inclusion of the terms 'testable' and 'falsifiable' which both the textbooks and manual also explicitly highlight as attributes of research hypotheses. However, it is noted that there is inconsistency in the emphasis of these attributes between the three resources. Whilst Reece *et al*. (2011) distinguishes between these two attributes, Starr *et al*. (2007) only mention testability in their definition and the BIOL 200 Toolkit resource manual mentions that research hypotheses are either testable or falsifiable.

The textbooks considered contain very little reference for information regarding alternative and null hypotheses. On the other hand, the BIOL 200 course resource included descriptions of these concepts. The BIOL 200 course is largely designed to assist students in designing and implementing research and a large portion of the manual focuses on the development of statistical analyses. The only reference to alternative hypotheses by Reece *et al*. (2011) in the introductory chapter of the textbook relates to alternative hypotheses as "hypotheses eliminated or falsified by testing". This reference to alternative hypothesis seems to align more closely with the definition of statistical alternative hypotheses than to alternative scientific hypotheses. Equally the BIOL 200 manual appears to describe alternative hypotheses in a similar light as Reece *et al*. (2011). Intriguingly however, the BIOL 200 manual refers to these as 'alternate' hypotheses rather than alternative hypotheses. Perhaps they use this term to make a distinction between alternative scientific and alternative statistical hypothesis, however this is not explicitly conveyed. While students' responses mirrored aspects of the definitions located in the BIOL 200 manual with regard to null and alternative hypotheses being opposites of each other or positive or negative states of the other, students particularly from the Westville campus and to a lesser extent Pietermaritzburg students highlighted that both null and alternative hypotheses displayed a relationship between variables. Few students however, seemed to connect the null and alternative hypotheses with statistical analyses even though these are explicitly stated in the BIOL 200 course manual.

Students' descriptions of predictions in the questionnaire probably showed the most consistency across all the scientific concepts both within and between the Pietermaritzburg and Westville campuses (Table 4). The majority of the students described predictions as expectations of what the results will be and yet this is not what is depicted in the two introductory textbooks or the BIOL 200 course manual. Predictions are explicitly defined in these as deductions or consequences from hypotheses that follow an 'if…then' reasoning (if the hypothesis is correct then we would expect this to occur). It appears that students fail to grasp the intricate connection between hypotheses and predictions. Instead, it appears from the student responses that they either view predictions as guesses of outcomes of experiments or they confuse predictions with statistical hypotheses.

A closer look at the defining of theories in the textbooks reveals that some inconsistency exists between the two textbooks. Whilst Starr *et al*. (2007) describes theories as a hypothesis, albeit a longstanding one, that can be used to make predictions about other phenomena, Reece *et al*. (2011) describe theories as having a broader scope than a hypothesis that is useful in deriving new specific hypotheses that can be tested (Table 9). Reece *et al*. (2011) also specifically mention the fact that theories are supported by a large body of evidence. Responses of individuals from the questionnaire seem to follow a similar description of theories depicted in the BIOL 200 course manual associated with how to write a good discussion. These predominantly view theories as a tool in the explanations of results. Students in their questionnaire responses fail to mention elements such as the linkages between theory and investigations, the broad scope of theories and their importance as a source for new hypotheses – all of which is highlighted in the introductory textbooks from their introductory biology course.

As with statistical hypotheses, elements of experimental design are not a primary focus in the introductory textbooks. Reece *et al*. (2011) mention the necessity of using control experiments and repeatability in general, whilst Starr *et al*. (2007) speaks generally about sampling error, the need for large sample sizes and repeatability, but do not explicitly describe or explain replication and randomization (Table 9). The BIOL 200 course manual refers to replication needing to be independent of each other and states that there is no clear indication of how big the sample size should be, however, the larger the sample size the greater the probability of reflecting the population more accurately. In reference to randomization the BIOL 200 course manual speaks about its role to reduce bias. This was clearly reflected in student responses to the question on randomization in the questionnaire. Although the manual defines what randomization does it does not explain how randomization is conducted in research. This appears to be an area of concern in undergraduate biology at UKZN, especially for students who are graduating with a belief in the necessity of randomization but the inability to apply it adequately to research investigations.

Discussion

Although this is merely a descriptive study, it marks an important first step towards revealing the types of conceptions that Life Science students at third year level at the University of KwaZulu-Natal hold. Identifying and analyzing misconceptions are a necessary prerequisite prior to any refining of science conceptions through instructional reform (Wendt and Rockinson-Szapkiw, 2014). Furthermore, it has been revealed that the identification and elimination of student misconceptions has resulted in better acquisition and understanding of science knowledge (Wendt and Rockinson-Szapkiw, 2014). Preconceptions held by students also influence how they respond, interpret and understand new information that they are confronted with (Fulmer *et al*., 2013). It is therefore important that instructors are aware of these preconceptions, and misconceptions regarding scientific concepts when exposing students to new information or new contexts. The identification of conceptions held by students also provides empirical evidence to assist in the development of curricular resources that may support and guide the implementation of instructional strategies to help bring about reform in conceptual understanding. This may be particularly useful to instructors who do not have any formal training in education but may also bring consistency in instruction of conceptions within and between campuses.

Student responses to an open-ended questionnaire

An analysis of the third-year level students' written responses revealed that students harbored varied responses for the majority of the concepts examined. In some cases, there were clear misconceptions whilst others there appears to be a limited or partial understanding. Alonzo and Gotwals (2012) have declared that misunderstandings of concepts are not necessarily simply misconceptions but lie along a continuum of student understanding known as learning progression. The construction of complex biological concepts occurs in phases in a scaffolded manner, building more complex concepts from more comprehensible ones (Brownell *et al*., 2014). It is however, concerning that students have not achieved a more comprehensive understanding of concepts by the final year of their undergraduate courses. It is suggested that this particular analysis be done at the introductory-level at the University of KwaZulu-Natal to determine both preconceptions, difficulties and misconceptions of these specific concepts. This will enable instruction strategies to be implemented that scaffold the development of conceptual ideas based on students' prior knowledge in order to ensure that students graduate with a solid foundation in core concepts of scientific inquiry.

The questionnaire focused on questions involving the research hypothesis, null hypotheses as well as the alternative hypothesis to determine whether students were able to distinguish between these concepts. In response to the research hypothesis question, students focused on the attributes research hypotheses (must be testable and/or falsifiable) have rather than what its function is. The scarcity of responses describing a research hypothesis as an explanation is concerning. This may be a consequence of students conducting investigations from laboratory manuals whereby research hypotheses are given and students do not require critical thinking skills in constructing research hypotheses. The lack of connection between what students do and why they do it in these particular laboratory setups may have led to these poor conceptions of research hypotheses. However, this study has the limitation that it only analysed students' written responses to questions. A more detailed investigation using interviews to help probe students' ideas may provide a more comprehensive description of students' understandings of research hypotheses.

Both the questions associated with null hypotheses and alternative hypotheses elicited a high proportion of responses associated with commonly held scientific descriptions of statistical hypotheses. In both instances students typically stated that they were the opposite of the other and in particular the Westville group of students placed a lot of emphasis on the relationship between variables in both scientific concepts. Generally, it is known that the null hypothesis and the alternative hypothesis are statistical hypotheses (Hutto, 2012), however, there was very little explicit mention of the association of both null and alternative hypotheses association with statistical analyses by the students. Laboratory exercises that predominantly focus on the development of practical techniques and the manipulation of apparatus, and that only include measurements of averages rather than the use of statistical analyses may produce a lack of connectivity between the null and alternative hypotheses with statistical analyses as well as a confusion between research hypotheses and statistical hypotheses.

The questionnaire purposefully did not ask what an alternative research hypothesis was or what an alternative statistical hypothesis was. This was to determine whether students held predominant ideas of alternative hypothesis associated to research or statistical hypotheses. These two types are very distinct and involved in different areas of scientific inquiry. Alternative research hypotheses are alternative explanations of phenomena which make predictions, whilst alternative statistical hypotheses are the complement to null hypotheses used in statistical testing of predictions (Romesburg 1981; Hutto, 2012). The students' responses predominantly described alternative hypotheses as alternative statistical hypotheses rather than alternative research hypotheses. Perhaps a lack of emphasis on alternative explanations to phenomena may have contributed to this biased view of alternative hypotheses.

Conceptions on predictions is another area where partial understandings have developed. The predominant theme that was displayed by students was that predictions are what they think, expect or predict to be the results of the investigations. This is a flawed approach as what students think an outcome will be, is irrelevant. Rather, a prediction is something that necessarily follows from a stated hypothesis. One cannot have a prediction without a research hypothesis and vice versa (Hutto, 2012). There appears to be a deficiency in students understanding of reasoning in the scientific inquiry process. The textbooks clearly highlight that predictions are deductions of hypotheses that use "if...then" logic. This essential element of predictions was absent from student responses, another shortfall that needs to be addressed through instruction and learning.

The question related to the role of theory in scientific investigations elicited a number of responses that include: used in background knowledge and previous research, brings explanation and understanding to results and the guiding of research. Few responses focused on the fact that theories have a broadness of scope and are able to explain a number of phenomena, or the fact that theories are a source for new hypotheses as outlined by the textbooks. However, the way the question was asked may not have elicited these types of responses. Perhaps asking one to define theories would have caused students to respond in a different manner. However, it seems that students did not carry the conceptual understanding of the relationship between theory and investigation and how they influence each other. In most cases it appears that they view theory as something which supports, explains, or backs up the results they obtained in an investigation rather than theory being used to guide investigations, produce new research hypotheses to test and that evidence obtained from investigations can modify or even cause the discarding of some theoretical ideas.

Questions related to experimental design included those on replication, sample size and randomization. A very varied response to the question related to sample size / replicate size existed. Some merely responded that it needs to be large whilst other elaborated on this by stating that it needed to be large to increase the reliability or accuracy of the results. Some students highlighted factors that may influence sample size and number of replicates. These included the type of research and the limiting factor of resources.

Whilst the majority of students from the Pietermaritzburg campus highlighted that sample size and replicate number is largely responsible for eliminating, reducing or avoiding bias, the greatest proportion of Westville students described that these aspects of experimental design were largely responsible for ensuring a greater accuracy and reliability of results. It appears that the Pietermaritzburg group may be confusing the function of replication with randomization.

The greatest consistency in responses within and across campuses was found in association with randomization. Students were asked whether randomization was necessary in investigations and then to explain why they thought it was necessary. Responses to the former part was a unanimous yes and the responses to the latter were largely concerned with the reduction, elimination or avoidance of bias. Although students seem to understand why randomization is necessary, this questionnaire does not highlight how randomization can be attained in investigations. This perhaps could be included in future examinations of students' conceptual understandings of randomization.

The influence of textbooks and course manuals on students' conceptions

Conceptions of students related to the null and alternative hypotheses, roles of theory, repetition and randomization largely reflect descriptions found in the BIOL 200 Toolbox manual. Interestingly, responses of students from the questionnaires seemed to show inconsistencies with descriptions of research hypotheses, predictions, and to a large extent theories existing in the Introductory Biology textbooks. This however, is not because these textbooks display discrepancies between them in the descriptions of these particular science concepts. Both describe research hypotheses as explanations and predictions as deductions or consequences of hypotheses, elements that were completely absent from student responses to these concept definitions. It appears then that although textbooks and course manuals have a role to play in developing students concept definitions, they are not the only influence in the construction of these scientific concepts.

Life Science faculty influence of students' conceptions

The School of Life Sciences in the University of KwaZulu-Natal have faculty who specialize in specific biological fields. These include: biodiversity and evolution, ecology, grassland science, biology, zoology, entomology, biochemistry, microbiology, genetics, cell biology and biotechnology. The number of faculty specializing in specific fields differs across campuses. A perusal of these highlight that a great proportion of faculty specialize in disciplines predominantly associated with field investigations (biodiversity, ecology and grassland science) in Pietermaritzburg (31%) compared to (7.1%) in Westville. Whilst less faculty focus specifically on biology, zoology and entomology in Pietermaritzburg (27.6%) than Westville (50%), similar percentages (41.4% and 42.9%) of faculty specialize in largely laboratory-based fields such as biochemistry, microbiology, genetics, cell biology and biotechnology.

Given that identical curricular are taught across campuses for the majority of Life Science courses and that the resources provided to students during these courses are the same, it is interesting that there are inconsistencies between students' responses to science concepts across campuses. One of the influences that might have led to students ending up with different conceptions across campuses may be associated with the differences in faculty teaching these particular courses and concepts. Differences in faculty epistemologies are often associated to the types of inquiry they engage with in their own research (Bonner, 2005). Different faculty members may therefore emphasize specific aspects of concepts more than others. The responses of students to sample sizes, replication and randomization may reflect different faculty emphasis on some of these through their instruction and associations with their own research. Equally, those faculty staff that conduct predominantly descriptive or correlational inquiry in their research may not emphasize conceptions of research hypotheses and predictions to the extent that an experimental faculty member might.

Limitations of study and future research

Although the work of this study is an important exploration into the possible conceptions that students have regarding hypotheses, predictions, role of theory and aspects of experimental design, work needs to be done to determine how prevalent these conceptions are throughout the undergraduate population at the University of KwaZulu-Natal. To assist in this regard, it is suggested that this exploration includes not only written responses but interviews that more deeply probe student understanding as it is possible that some students may not have written down their full conceptions in answering the open-ended response questionnaire.

The results of this particular study have helped ascertain the types of conceptions students at third year level at the KwaZulu-Natal hold and are necessary for further research aimed at conceptual change. Although caution must be taken in the generalizing of such results, they do however, provide foundational ideas that could assist both in developing instructional strategies to promote conceptual change as well as the development of instructional materials that would greatly benefit from the understanding of student and teacher conceptions in these areas of science.

The next step would be to explore the underlying reasons for students incomplete or misconceptions on hypotheses, predictions, the role of theories, samples size and replication and randomization. Future research which is beyond the scope of this study may include the investigation of the influence of instructor conceptions, differences in instructional strategies and the influence of different types of assessments in eliciting appropriate responses to conceptions.

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Table 1: The percentage of 3rd year Biology participants that included particular characteristics in their definition of a research hypothesis.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
An explanation	3.6	6.0
It is a statement	50.0	50.0
A question	25	16.0
Educated guess	3.6	10
Expected outcome or result	11	20
Must be falsifiable	18	12
It is tested or must be testable	25	28
Associated with experiments	7.1	36
Based on observation	25	22
Makes a prediction	7.1	10

Table 2: The percentage of 3rd year Biology participants that included particular characteristics in their definition of null hypothesis.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
A statement	29	36
An expected outcome	21	16
A negative hypothesis or the opposite of the hypothesis / alternative	50	48
Must be falsifiable	21	10
It is tested or must be testable	21	38
Associated with experiments	14	24
Relationship of no difference	14.3	48
Mention of statistics	3.6	18

Table 3: The percentage of 3rd year Biology participants that included particular characteristics in their definition of alternative hypothesis.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
A statement	32	26
Another explanation	11	4
Opposite to the null hypothesis / the hypothesis in a positive state	57	58
Must be falsifiable	7	0
It is tested or must be testable	21	14
Associated with experiments	11	8
Relationship showing a difference or having an effect on	11	30
Accepted if the null is rejected	18	6
Mention of statistics	3.6	8

Table 4: The percentage of 3rd year Biology participants that included particular characteristics in their definition of a prediction.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
A statement	35.7	22
A guess	10.7	8
What we think, expect or predict will happen or be the outcome of the results	82.14	92
Expect results of experiment to be	35.7	48
Linked to the hypothesis	21.4	12

Table 5: The percentage of 3rd year Biology participants that included particular characteristics in their description of the role of theory in research.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
It provides background information and previous knowledge and research	57	48
It guides the research	14.3	16
It brings explanation and understanding	35.7	14
It is used to back up or support results	7.1	14
Used in reasoning	0	2
Compare results to	0	12
It is supported by numerous testing	3.6	10

Table 6: The percentage of 3rd year Biology participant's reference to what replication or sample size is needed.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
Depends on study or research	14.3	2
Must be large	32.1	12
Representation of whole population	7	14
Large to ensure accuracy or reliability of results	3.6	18
Large but depends on resources	3.6	6
Replicates >3	14.3	24
Other amount of replicates > between (5-10)	10.7	8
No answer or off track	14.3	16

Table 7: The percentage of 3rd year Biology participant's reference to characteristics associated with why replication is necessary.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
Reduce, eliminate or avoid bias	60.7	38
Improve accuracy or reliability	32.1	56
Not fluke (Pmb), not due to chance (Westville)	28.6	10
Reduce errors	14.3	16
Reduce influence of confounding factors	3.6	10
Reference to statistics	7.1	4
Experiments	21.4	18

Table 8: The percentage of students reference to phrases associated to the reasoning for randomization in experimental design.

	Percentage of individuals from the Pietermaritzburg campus (%) (n = 28)	Percentage of individuals from the Westville campus (%) (n = 50)
Reduce, eliminate or avoid bias	60.7	64
Equal chance of being selected	7.1	12
Better representation of population	14.3	6
Confused with controls or replication	7.1	4

Table: 9 Definitions of concepts obtained from the prescribed introductory course textbook and second year biological sciences toolkit for BIOL 200

	Concept definitions derived from two popular textbooks used in the Introductory course at UKZN	**Concept definitions derived from the Biological Sciences Toolkit for BIOL 200**
Hypothesis	"In science a hypothesis is a tentative answer to a well-framed question – an explanation on trial. It is usually a rational accounting for a set of observations, based on the available data and guided by inductive reasoning…First a hypothesis must be testable; there must be some way to check the validity of the idea. Second, it must be falsifiable; there must be some observation or experiment that could reveal if such an idea is actually not true… A hypothesis gains credibility by surviving multiple attempts to falsify it…." (Reece et al. 2011) "A hypothesis is a testable explanation for a natural phenomenon" (Starr et al. 2007)	"A scientific hypothesis is a proposed explanation for an observation. It is formulated through inductive reasoning A good hypothesis: - Addresses a specific question being asked. - States a feasible, plausible explanation for observations - It is testable or falsifiable. A hypothesis can be supported or falsified, but it cannot be proved."
Alternative hypothesis	"…. While alternative hypotheses are eliminated (falsified) by testing" (Reece et al. 2011)	In the manual this falls under statistical concepts: "Your biological hypothesis (called the alternate hypothesis, or H_A) makes a statement of the general form of 'a is different from b' or 'a

		is related to b' or 'a increases with b'…The hypothesis of biological interest is the alternate hypothesis."
Null hypothesis	No mention by Campbell Biology in the introductory chapter in the theme of life: concept: Studying nature, scientists make observations and then form and test hypotheses.	"Statistical tests evaluate what is called the "null hypothesis (represented by H_0), this null hypothesis is the only hypothesis that can be tested statistically. The null hypothesis is the 'not different than', 'not related to', 'does not increase with', 'is the same as' version of the biological hypothesis…The null hypothesis is the contrasting form of the biological hypothesis and is what statistical tests evaluate."
Predictions	"When using hypotheses in the scientific process, deductions usually take the form of predictions of experimental or observational results that will be found if a particular hypothesis (premise) is correct. We then test the hypothesis by carrying out the experiments or observations to see whether or not the results are as predicted. This deductive testing takes the form of "If…then" logic." (Reece et al. 2011)	"A prediction is a rigorous statement forecasting what will happen under specific conditions. It is an assertion that is a logical consequence of your hypothesis or theory."

<table>
<tr><td></td><td>A prediction is a statement of some condition that should exist if the hypothesis is correct. Making predictions is called the if-then process, in which the “if” part is the hypothesis and the “then” part is the prediction” (Starr et al. 2007)</td><td></td></tr>
<tr><td rowspan="2">Theory</td><td>“First, a scientific theory is much broader in scope than a hypothesis. Secondly, a theory is general enough to spin off many new specific hypotheses that can be tested. And third, compared to any one hypothesis, a theory is generally supported by a much greater body of evidence. In spite of the body of evidence supporting a widely accepted theory, scientists must sometimes modify or even reject theories when new research methods produce results that don’t fit.” (Reece et al. 2011)</td><td rowspan="2">No mention of theory in particular. However, it mentions in qualities of a good discussion.
- reminds reader of the key results
- uses and cites relevant literature to explain results and put results into a bigger context
- explains the mechanisms underlying the results
- puts the results into context
- critical assesses results in light of original objectives and hypotheses
- states whether hypotheses have been supported or refuted
- explains potential reasons for results that contradict what is found in the literature
- ideas for future work to expand on or enhance your study or findings</td></tr>
<tr><td>“A scientific theory is a long-standing hypothesis that is useful for making predictions about other phenomena.” (Starr et al. 2007)</td></tr>
<tr><td></td><td>Reece et al. (2011) only refers to controlled experiments and repeatability.</td><td>“Replicates are a set of samples that are manipulated and/or</td></tr>
</table>

Replication	Although Starr et al. (2007) does not speak about replication and randomization, they do include a section on analyzing experimental results which include sampling error, probability, statistical significance and bias in interpreting results. "Sampling error can be a substantial problem with a small subset, so experimenters try to start with a relatively large sample and they typically repeat their experiments."	measured in the same way. Replicates should be independent of each other. There is no set answers to how big your sample should be or how many samples and/or replicates you need. However, in general, the more you sample and the more data you collect, the greater will be the probability that your observations will reflect reality, that your sample will be representative of the population you are interested in."
Randomization		"Randomization refers to the random selection, assignment, and handling of samples and treatment groups. Randomizing your sample of a population will minimize bias. Sampling bias is a serious flaw that can lead to a very much distorted impression of the population that is being sampled. A biased sample of a population is any sample in which some individuals have less chance of being sampled than do other individuals."

Appendix 1: BIOL 390 Biology/ecology research project

As a precursor to the Biol 390 course this questionnaire has been formulated to determine your understanding of essential aspects of research in the Life Sciences. It will also be used to assess your progress in these understandings as you embark on a mentored journey with an individual staff member throughout the duration of this course.

1 What prerequisite module(s) have you received credits for? (Please tick the relevant box(es):

□ STAT 130 □ BIOL 200 □ BIOL 300

2 What is a research hypothesis?

3 What is a null hypothesis?

4 What is an alternative hypothesis?

5 What is your understanding of a prediction?

6 What role does theory place in research?

7 What type of replication or sample size do you need to conduct your research?

8 Why is replication necessary?

9 Do you need to consider randomization in your experimental design?
Why / why not?

CHAPTER 6

Assessing conceptual understanding through mentored research experiences in undergraduate students

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Abstract

The purpose of this case study was to elucidate conceptual understandings of the scientific process through the analysis of mentored third year level research projects. Biology 390 projects were analyzed from 2012 (n = 26 students), 2013 (n = 46 students) and 2014 (n = 34 students). Journal formatted project write-ups were examined for reference to aims, objectives, hypotheses and predictions. Students' ability to appropriately apply experimental design was also assessed, only in those projects where students conducted experimental research, by documenting their use of replicates, sample size, randomization and controls. Conceptions of the broad nature of the scientific process and scientific inquiry were also noted by surveying all project introductions, discussions and conclusions for evidence of students' ability to link their research into the greater network of scientific knowledge.

There was an overemphasis in the use of statistical hypotheses compared to scientific hypotheses by BIOL 390 students in their project write-ups. Many students used predictions inappropriately and a large majority of students failed to incorporate critical aspects such as randomization and controls into their experimental designs. Explicit didactic discussions by mentors with their students are necessary in order to improve these conceptions of the scientific process. It is suggested that mentors become familiar with both learning theories and common misconceptions associated with the nature of science and scientific inquiry so that they are able to apply these to their mentoring approaches of students conducting research projects.

Keywords: *Research experiences, mentors, research design, hypotheses*

Introduction

The field of biological sciences has not only experienced a rapid expansion in knowledge over recent decades (Cheesman *et al.*, 2007; Hoskins *et al.*, 2011) but has also undergone rapid progress in biological research as it has taken on a more multidisciplinary nature (National Research Council [NRC], 2009). There has been a global response that has appealed for a revolutionizing of undergraduate biology education to accurately reflect and keep in step with the rapidly changing nature of modern biology (Labov *et al.*, 2010). Numerous reform documents have called for a transformation in science teaching and learning in order to address the needs of the 21st century biology undergraduate (American Association for Advancement of Science [AAAS], 1989, 2011; National Research Council [NRC], 2003). A recent document: The Vision and Change: A call to Action (AAAS, 2011) outlines a vision that foresees an aligning of undergraduate teaching with current trends in biological research (Woodin *et al*., 2009; 2010). This document advocates the reduction in the volume of content knowledge and promotes the application of core concepts across the undergraduate curriculum (AAAS, 2011). It also stresses the development of five core competencies, namely: the ability to apply the process of science, the use of quantitative reasoning, understanding the multidisciplinary nature of science, communication and collaboration and understanding the relationship of science and society (AAAS, 2011).

The traditional style pedagogy does not adequately lend itself to the development of these competencies (Thomson *et al*., 2013). Thus an alteration in learning experiences is necessary in order that these competencies be developed in our current undergraduates. According to the Vision and Change document this requires the implementation of student-centered learning strategies which allow for the active involvement of students in open-ended inquiry, associated with learning contexts that encourage cooperation (AAAS, 2011). There are a number of innovative teaching strategies that provide active student-centered learning opportunities. One of the suggested innovations in pedagogy is the introduction of research experiences throughout the undergraduate curriculum.

Over the past decade faculty have been innovative in their development of authentic research experiences that enable the realization of student-centered learning and the development of core competencies to undergraduates at all levels. These ensure that students experience authentic science at an early phase in their studies rather than just those select few individuals who in their undergraduate exit year show an interest in furthering their career development in biological research (Russell *et al*., 2015). Idealistically, a research experience would expose students to the full range of scientific practices, but this is very rarely practical under the constraints of time, infrastructure and mentor availability (Auchincloss *et al*., 2014). However, this does not negate the fact that meaningful research experiences can be achieved. A variety of research experiences have been designed by faculty that vary in their depth, duration, technical difficulty and the amount of collaboration and guidance according to the institutions resource availability and the maturity of the students (AAAS, 2011). By focusing on the core competencies to be developed, as outlined by the Vision and Change document, a number of meaningful research experiences have been created.

These research experiences range from designing activities that provide students with the opportunity to read and evaluate journal articles, to courses that provide opportunities for major and non-major students to participate in guided or independent research projects (AAAS, 2011). CURES (course-based undergraduate research experiences) were developed in response to the demand for student research to be introduced at the introductory levels targeting all students enrolled in the course (Auchincloss *et al*., 2014). ICURE (integrated course-embedded undergraduate research experience) was another form of research experience that aimed to bridge courses and address the development of the core competency: the multidisciplinary nature of science (Russell *et al*., 2015). UREs (Apprentice-style undergraduate research experiences) allowing for the closer collaboration and communication with professional scientists have also been developed, but may require a greater investment of financial and faculty resources (Wei and Woodin, 2011).

Much emphasis has been placed in numerous undergraduate reform documents on the enormous value of undergraduate research experiences. This has been based on an emergent body of research that has highlighted benefits afforded to students who engage in research opportunities (Kardash, 2000; Seymour *et al*., 2004; Lopatto, 2007; Hunter *et al*., 2007; Russell *et al*., 2007; Auchinloss *et al*., 2014). These highlighted benefits broadly fall within the areas of disciplinary skill development, cognitive development, professional development and personal development (Lopatto, 2004; Lopatto, 2006; Hunter *et al*., 2007; Lopatto, 2010; Thiry and Laursen, 2011).

Disciplinary gains in practical and technical skills as well as cognitive skills have been shown to be one of the greatest benefits for students engaging in research experiences (Zydney *et al*., 2002; Lopatto, 2006). However, the literature has shown that research experiences can also produce gains in professional development and advancement (Lopatto, 2004; 2006; 2010). Gains in professional development include a clarification or a confirmation in the pursuit of a career in science. These gains come through the development of better understandings of the research process and an appreciation of the thought processes and demands presented to professionals whilst tackling scientific problems (Lopatto, 2006). Professional advancement has been shown to be positively affected through students' participation and interaction with a community of practicing professionals, mentors, postgraduates and peers (Bender *et al*., 1994, Lopatto, 2010). Research experiences may also provide the benefits of publishing or presenting their work to the scientific community leading to further professional advancement (Lopatto, 2006).

Whilst faculty perceive skill development and professional development as the primary benefits to research experiences, evidence has shown that personal gains rank high on students list of benefits from research experiences (Lopatto, 2003). Personal gains documented include personal growth in understanding one's abilities (Lopatto, 2006), ability to work and think independently (Lopatto, 2004; 2003), tolerance of obstacles (Lopatto, 2004; 2007) and experiencing a sense of accomplishment at the end of a research experience (Lopatto, 2006). All these personal gains lead to a growth in self-confidence that enables students to willingly tackle more demanding research.

What characterizes the research experiences that produce these essential gains in personal and professional developments in students? Auchincloss *et al*. (2014) conducted a comprehensive study of CURE's as well as other internship programs to determine what characteristics are attributed to research experiences that produced these student gains. They highlighted five dimensions that are essential attributes to authentic research experiences: the use of real world scientific practices, discovery, broader relevance or importance, iteration, and collaboration (Auchincloss *et al*., 2014). These dimensions essentially are traits which reflect research in the real world. Working scientists are involved in a number of activities as they conduct their research. These include asking questions, developing and assessing models, formulating and framing hypotheses, designing studies and choosing appropriate methodologies (NRC, 1996).

Real world scientists do not follow a single universal step-wise method as portrayed in many textbooks and laboratory activities in undergraduate curricula. There are different approaches to inquiry in the sciences. Some involve inductive science leading to generalizations that discover and describe patterns found in the real world (Murray, 2001; Haig, 2005b). These are often known as discovery or descriptive studies, often essential in the early stages of development of a field in science (Mayr, 1997; Murray, 2001). Other scientific inquiry involves hypothesis-led deductive science that seeks explanations for non-random patterns. All aspects of inquiry are an integral part of the process of science and fit together in the great body of scientific knowledge (Haig, 2005a; Kosso, 2009). Real scientific research involves challenges that are overcome through critical thinking and drawing on of expertise of fellow scientists even across disciplinary boundaries. Scientists are faced with decisions in choosing the most appropriate approaches, methodologies, statistical models and techniques. Real world research also involves dealing with unexpected results and experimental failures as well as the proposing of alternative explanations, approaches and methodologies in the iterative world of science. It is essential that authentic research activities provide opportunities for students to experience these attributes of science and develop skills in dealing with the 'messiness' of science (AAS, 2011; Auchincloss *et al*., 2014; Bell *et al.*, 2003).

Traditional research experiences have proceeded on the assumption that students will learn about the scientific process by merely participating in science (Bell *et al*., 2003). Research that has been conducted to improve Nature of Science conceptions through authentic science activities have highlighted that explicit approaches to instruction are far more effective than implicit approaches (Abd-El Khalick and Lederman, 2000; Khishfe and Abd-El Khalick, 2002; Lederman, 2007). Students that are engaged in scientific inquiry alone do not necessarily enhance conceptions of NOS (Bell *et al.*, 2003; Schwartz *et al*., 2004). According to Schwartz *et al.* (2004) an explicit-reflective approach is an essential feature that establishes significant gains in conceptual understanding. Well-designed authentic research experiences are meaningless in the absence of explicit-reflective support, guidance and advice from experienced researchers throughout the research experience. "The only effective way to learn to do science is by doing science, alongside a skilled and experienced practitioner who can provide on the job support, criticism and advice (Hodson, 1998, p. 200).

The role of a mentor or facilitator should be to assist students not only in project design but to highlight the process of science throughout the research experience. In other words, mentors need to emphasize the bigger picture or the 'architecture' of science (Kosso, 2009; Bell *et al*., 2003). A large part of this process is to stress how the crucial elements like hypotheses, theories, predictions and evidence fit together (Kosso, 2009). It has been highlighted that much confusion exists regarding these components in the scientific method, particularly in the area of hypotheses and predictions (McPherson, 2001; Hutto, 2012). Confusion in the use of terminology have resulted in many misusing and exchanging scientific hypotheses with statistical hypotheses (Hutto, 2012). The result is a bulk of research dwelling excessively on statistical hypothesis testing at the expense of research hypothesis testing (Hutto, 2012). Statistical hypothesis testing is not the same thing as research or scientific hypothesis testing (Hutto, 2012).

Delineating and clarifying the role that scientific hypotheses and statistical hypotheses play is essential in developing an accurate understanding of the scientific process as a whole. Statistical hypothesis testing is used to uncover an observation or regularity that is not likely a chance occurrence (Hutto, 2012; McPherson, 2001). Statistical hypothesis testing usually involves two outcomes: the alternative statistical hypothesis and the null statistical hypothesis (Hutto, 2012). The type of reasoning associated with statistical hypothesis testing is inductive in nature resulting in the formulation of inductive generalizations. Although 'fact-finding' using statistical hypothesis testing is an essential part of the scientific process it does not, as often portrayed to students, entail the entire process of science. It is in fact merely the observational element of the scientific process (Hutto, 2012).

Scientific hypotheses, sometimes known as biological or research hypotheses, are associated with deductive science. They are potential explanations for why the non-random patterns exist (Hutto, 2012). Contrary to statistical hypothesis testing, a number of alternative explanations may exist to explain a pattern. These are known as alternative scientific hypotheses. In deductive science predictions are formulated to assist in distinguishing between potential alternative scientific hypotheses. Predictions are logical consequences associated with specified scientific hypotheses. They are ‘if-then’ statements that must be true if the hypothesis is true (Hutto, 2012). It is impossible to test predictions if they have not arisen from a scientific hypothesis. The testing of predictions may involve observation, comparative or experimental evidence (Hutto, 2012). This notion emphasizes the fact that one does not need to do experiments or make use of statistical hypothesis testing in order to test scientific hypotheses (Eberhardt, 2003). Some of the most important scientific achievements have been accomplished without the use of experiments and statistical testing (Mayr, 1997).

Misappropriation, misuse and exclusion of key components of the scientific process can lead to a diluting of the effectiveness of science (McPherson, 2001). When students associate hypotheses with ‘what they think will happen or a guess to a yes-no answer’ and predictions with ‘guesses of outcomes of experiments’, there is a clear indication of a misunderstanding of the process of science (Hutto, 2012). These misunderstandings are often generated because hypotheses and predictions are used completely detached from the broader framework of the overarching scientific ‘architecture’ (Kosso, 2009; Hutto, 2012; Bell *et al*., 2003).

Another area of persistent concern is students understanding and misappropriate use of experimental design, analysis and interpretation of data (Zolman, 1999). Flawed biological research is rife in the literature as a result of conclusions obtained from experimental designs that contain confounding factors as well as the inappropriate use of statistical models (Zolman, 1999). Often these confounding factors are related to neglecting the application of randomization to experimental treatments, overlooking the necessity for including a control group or condition and the inappropriate application of statistical models to specific data (Zolman, 1999). The errors in experimental design may also be attributed to the lack of clarity or failure to postulate a scientific hypothesis. A study cannot be designed or a statistical test performed in the absence of a scientific hypothesis (Guthery *et al*., 2001). It is the scientific hypothesis that guides the design of a specific investigation. It determines what variables should be isolated, what variables should be manipulated and measured and what tests should be performed (Guthery *et al.*, 2001; Lawson, 2010). Crucial accurate experiments are essential if one intends on eliminating alternative potential explanations (Platt, 1964; Zimmerman, 2000).

Both descriptive and hypothesis-led studies; scientific and statistical hypotheses; observational and experimental evidence and inductive and deductive reasoning are essential in the process of science (Mayr, 1997). However, it is critical that each of these are used appropriately and accurately. It is necessary that undergraduate students graduate with the skills and understanding that enable them to grasp where in the greater context of science they are operating when they are conducting research.

Literature associated with authentic research experiences have largely been conducted through interviews on the perceptions of student gains following engagement in research experiences (references). This study however, attempts to provide evidence-based research on students' ability to apply conceptual understandings of hypotheses, predictions, experimental design to actual research contexts under the supervision of faculty mentors. We expect that students will predominantly use statistical hypotheses in their project write-ups rather than scientific hypotheses and predictions. In addition, we investigate whether differences in these conceptual understandings are exhibited between different cohorts of students.

Methods

Context of learning environment

The study took place in a relatively large, research university (University of KwaZulu-Natal) which exists over three campuses in southern Africa. The particular course analyzed in this study namely: Biology/ecology research project (BIOL 390), is offered to students on two campuses; Pietermaritzburg and Westville. The course is designed to introduce students to independent research in the biological and/or ecological sciences in their third year of undergraduate study. It aims to improve problem-solving capabilities as well as increase their interest and enthusiasm for subject matter. Students are offered a number of small independent research projects provided by individual faculty from which to choose from. These projects are then supervised by these staff members who mentor students through the process of project conception, design, execution and reporting. Different faculty participate in this course within and between campuses.

The prerequisite courses that are required to register for BIOL 390 are either the STATS 130 course or the BIOL 200. The STATS 130 course introduces students to a wide range of statistical techniques required for the analysis of quantitative data whilst the BIOL 200 course covers hypothesis and prediction generation, experimental and sampling design, statistical analysis as well as training in scientific writing.

The majority of biology courses in the undergraduate curriculum prior to this course are primarily lecture-based with laboratory sessions offered to students as opportunities to learn techniques and verify concepts taught in class. This BIOL 390 course is the first opportunity for students to attempt an independent project whereby they are required to generate hypotheses, predictions, and reason through a study, while under the supervision of a faculty member.

Data collection and analysis

Data collection involved analyzing the final write-ups of the BIOL 390 projects. Only research projects from the Pietermaritzburg campus was selected for this particular investigation. In the second semester 26 students in 2012, 46 students in 2013 and 34 students in 2014 conducted and completed the course in the Pietermaritzburg campus. Project write-ups written in journal format were analyzed from each of these students. Data collection consisted of reading through individual third year Biology 390 projects from each year. Firstly, the introductions from students BIOL 390 project write-ups were examined and it was noted whether students referred to terms such as aims/purpose, objectives, hypotheses and predictions. Where the term hypothesis was used by students, it was further categorized into whether it was stated as a scientific hypothesis or a statistical hypothesis.

When investigating aspects of experimental design, only projects that were experimental in nature were selected and examined. The methods section of the BIOL 390 project write-ups was examined for reference to the use of controls, repetition, sample size and randomization. Where the term randomization was used it was further analysed whether students mentioned the manner in which they randomized in their particular experimental design.

Lastly, the discussion and conclusion sections of the BIOL 390 project write-ups were examined to determine students' ability to reason using evidence obtained in their results. Specific elements were examined such as their ability to explain their results and support and compare their results with previous research. It was also noted whether students accepted or rejected hypotheses or predictions and whether students mentioned the fact that their results provided evidence for or supported research in their particular area of study. Other attributes that were examined included whether students mentioned features such as confounding factors, areas of improvement of their particular investigations, application of their results and suggestions of future research i.e. alternative hypotheses to be tested or alternative methodologies.

Data consisted of "yes" or "no" answers inputted into an excel spreadsheet under the headings related to the above mentioned topics. A count was done for all the "yes" answers for each topic across the years 2012 - 2014 and a percentage was calculated. These percentages were then presented graphically.

Results:

Types of projects offered

The types of projects offered to students for their third year projects by faculty were divided into three categories namely: descriptive studies, field experimental studies and laboratory experimental studies. Less than 20% of the 104 projects across all three years were descriptive in nature (Fig 1). The remainder were experimental studies with a slightly higher proportion of the projects in 2012 (42.3%) and 2013 (56.5%) falling into the laboratory experimental study category whilst a slightly higher proportion of the projects in 2014 (47.1%) were offered as field experimental studies.

Aspects examined in the introductions

The majority of students (>80% of the 104 projects) across all three years provided either an aim or purpose in their BIOL 390 project write-ups. More students in 2013 provided objectives (41%) in their project write-ups than in the other two years. Those students that included hypotheses in their write-ups ranged from between 65% in 2013 and 50% in 2014. The percentage of projects that contained predictions was found to be greatest in 2012 (62%), with half of the students using predictions in 2014 and less than 40% in 2013. Interestingly, this seems to be related to students predominantly using statistical hypotheses with objectives or merely solely statistical hypotheses without predictions.

Provision of a theoretical framework was recorded if students provided detail of the broader scope of knowledge in their introduction. In other words, how their research fits into the larger context of research. This may take the form of theoretical or hypothetical ideas, previous research focused in the specific area of research or generalized patterns of phenomena. The results indicate all three years showing similar results in this regard. Between 54% and 61% of students indicated an ability to successfully portray how their research is positioned in the greater context of knowledge.

The results indicate the students are competent at setting the scene and including the use of previous research with more than 70% of students in all three years including these aspects in their introductions. In particular, 2014 shows over 90% of students including these aspects in the project write-ups.

Hypotheses and predictions examined in greater detail

A closer examination of students' use of hypotheses revealed that overall less than 30% of students across all three types of studies and all years used scientific hypotheses in their project write-ups. With the exception of the field experimental studies in 2013, results indicated that a higher proportion of all the write-ups contained statistical hypotheses rather than scientific hypotheses. Interestingly, in 2013 results revealed a higher proportion of students using scientific hypotheses compared with statistical hypotheses in field experimental studies but the opposite was observed in the laboratory studies.

Descriptive studies were characterized by lacking scientific hypotheses except in 2012 where 20% of the project write-ups contained a scientific hypothesis. In 2013 none of the descriptive studies contained any hypothesis whatsoever whereas in 2014 half of the students used statistical hypotheses in their project write-ups. Predictions were found in 40% of the descriptive studies in 2012 and this increased to 66.7% in 2014. While 60% and 50% of the students in 2012 and 2013 respectively included neither hypotheses nor predictions, it was found that this percentage was reduced to 16.7% in 2014

Examination of the field experimental study write-ups highlighted that 80% of the students in 2012 included hypotheses. However, most of these were written as statistical hypotheses (Figure 3). In 2013 field experimental studies contained predominantly predictions (80%) with less than 40% including hypotheses in their project write-ups. In 2014, 56.3% of the students did not include hypotheses and those that did were found to predominantly use statistical hypotheses. In 2012 all field experimental write-ups contained either hypotheses or predictions or both. However, in 2013 and 2014 about a quarter of the students neither used hypotheses or predictions in the field experimental studies.

The laboratory experimental study write-ups revealed a greater percentage of students using hypotheses in all three years compared with the field experimental studies. It was found that similar percentages of students in 2012 and 2014 used hypotheses in their project write-ups (63.7%; 58.4% respectively). Again about 70% of these hypotheses corresponded with statistical hypotheses rather than scientific hypotheses. In 2013, although slightly over 88% of students included hypotheses in their write-ups, 73.1% were noted to be written as statistical hypotheses. Correspondingly, only 34% of students in 2013 included predictions. This indicated that although students provided hypotheses, not all of them simultaneously provided predictions.

Experimental design applied to students' research projects

Only those studies that conducted experimental work was selected (n = 21 in 2012; n = 44 in 2013 and n = 28 in 2014) to examine students understanding and use of experimental design. It is clear that students and mentors believe in the necessity of the use of statistics in the analysis of their results with more than 90% of the students using statistical analyses in their project write-ups in all three years.

The majority of students (>70%) mentioned their use of replicates and sample size in their experimental project write-ups across all three years. However, mention of controls and randomization were less frequently observed in students' methods sections. Only 52.4% of the research projects mentioned controls in 2012 down to 39.3% in 2014. Equally, less than 50% mentioned the use of randomization in their experimental design. Those that did predominantly stated that they used randomization but only 11.4% in 2013 and 3.6% in 2014 described how they randomized in their experimental designs.

Reasoning in the discussion and conclusion

The majority of the students across all three years recognized the need to explain their results in the discussion (Figure 5). They also made use of references to help clarify and support their explanations. There was definitely an increase in the percentage of students who did this from 54% in 2012 to over 85% of the students in 2013 and 2014. The majority of the students also included other research already performed on their problems under investigation. These either included studies that used different species, populations or techniques.

Interestingly, the percentage of students including either the acceptance or rejection of hypotheses or predictions in their discussions increased from 38% in 2012 to 68% in 2014. The area of greatest concern is that less than 40% of students in 2012 and less than 30% in 2013 and 2014 (figure 5) clarified that their results supported any theoretical ideas or even suggested how their research added to the greater body of scientific knowledge.

Another area of concern was students lack of inclusion (>40%) in mentioning possible confounding factors or improvement that could be done in their particular research (>50% although there was an improvement in the percentage of students including this in their project write-ups from 2012 – 2014). Although only 46% included suggestions for future studies in 2012, results indicate that this year showed a higher percentage of students including this in their research project write-ups than in 2013 and 2014 (11% and 21% respectively). Suggestions of future studies was noted as being suggestions that may test alternative explanations or use alternative methodologies to test the research problem. Although many of the research projects focused on areas of research concerned with invasive plants, pests or management less than 20% across all three years included in their discussions or conclusions how their particular results could be applied to management in these areas of interest.

Overall, the results indicate that students are skilled in the explanation and supporting of the results they obtained in their research. But the linkage between results and the theoretical framework is largely absent.

Discussion

Types of studies offered by faculty

Descriptive, experimental field and experimental laboratory studies all play a different but vital role in science (McPherson, 2001). Opportunities for students to conduct research outside of the traditional laboratory setups may bring both renewed enthusiasm for biological research and also challenges to conceptual misunderstandings regarding the nature of the scientific process (Bell *et al*., 2003; Auchincloss *et al*., 2013).

Experimental field studies provide opportunities to develop skills and critical thinking regarding experimental design. It is not always possible to control variables in the field and thus students are exposed to challenges and decisions in both the design of their studies and the interpretation of their results. Descriptive studies offer the opportunity to challenge misconceptions regarding the Nature of Science (NOS). With the method of science typically presented to students throughout their undergraduate careers as science as an experimental endeavour, many students hold fast to the misconception that experimental investigations are the only way to do science. Bell et al., (2003) who conducted research on understandings of the Nature of Science indicated that a particular student showed an altered view of how science is done when exposed to a scientific apprenticeship that was largely observational in nature. However, this occurrence was not merely due to the observational nature, as other students who conducted observational apprenticeships did not exhibit changes in their misconceptions and typically adhered to the view that there is a single scientific method that is experimental in nature (Bell *et al*., 2003). The key difference between these student apprenticeships was the role that the mentor played in challenging that one student's misconceptions through explicit discourse regarding the Nature of Science throughout the apprenticeship (Bell et al., 2003). This indicates that providing a different type of research project such as a descriptive or field experimental study is not enough to challenge students' misconceptions. The mentor performs a vital role in challenging these misconceptions through explicit-reflective mentoring.

Students' ability to introduce their research in their BIOL 390 projects

The introduction of most journal articles contains an overview of what is being investigated and why. This area of an investigation requires just as much critical cognitive thinking as needing in the analysis and interpretation of the results and is in fact critical to the success of the research. It requires a complete conceptual and propositional analysis surrounding the research topic and involves the understanding and connecting of relationships between different pieces of knowledge (Ford, 2000). By constructing this analysis one has a better understanding of what has already been accomplished, insight into what might still need to be done and whether theoretical ideas can be extended or whether they require refining.

Results from this study indicate that the majority of students include either an aim or purpose in their research project write-ups. Most of the students have typically followed a format of a written introduction that includes some background knowledge about the research topic and then finally stating their hypothesis, predictions and sometimes objectives at the end.

The results indicate that the students are very good at setting the scene by providing background knowledge, definitions of concepts and providing other research on the topic (although sometimes irrelevant). Many have a good theoretical framework which starts with the bigger picture and narrowing it down to their specific research context. It appears that mentors have spent time assisting students in laying a good foundation for the research by insisting on the inclusion of previous work and theories that have been tested that are associated with their particular research. However, where students seem to be lacking is their ability to take a further cognitive step by stating how their work fits within the framework of scientific inquiry. Hypotheses and predictions are often just precariously hitched onto the end of their introductions, as if they were merely an afterthought.

Students use of scientific hypotheses, statistical hypotheses and predictions

Although 50-65% of the students across the three years stated hypotheses in their introductions, results indicate that there is an overemphasis in the use of statistical hypothesis at the expense of scientific hypotheses. In most instances statistical hypotheses were stated in the absence of scientific hypotheses. This indicates that students may be confusing statistical hypotheses with scientific hypotheses. They may think they are stating scientific hypotheses but are in fact not. One cannot make decisions about experimental design and statistics if one has not clearly defined a scientific hypothesis.

Predictions are also used by many students in the absence of hypotheses. This is an irrational approach to using predictions. Predictions have to be linked with hypotheses otherwise they are redundant. The sole use of predictions may indicate that these students are confusing predictions with statistical hypotheses and do not fully grasp the role of predictions. Predictions are associated primarily with deductive science which means they need to be derived from a well-defined scientific hypothesis (Hutto, 2012). One cannot have one without the other.

A large proportion of students stated predictions following statistical hypotheses. Although they indicate a perception that predictions must follow hypotheses, it appears that they are rote following the recipe of the scientific method rather than a complete understanding of what predictions are and their role in deductive science. McPherson (2001) associates the misuse of predictions with a misinterpretation of the hypothetico-deductive method. Predictions are not 'guesses or expected outcomes of experiments' but are rather logical deductive consequences derived from a scientific hypothesis that require testing (McPherson, 2001; Hutto, 2012). It is important for students to recognize that the word 'prediction' that they commonly use after stating statistical hypotheses is in fact rather a 'probabilistic expected outcome' (Murray, 2004).

Students' description of experimental design in their BIOL 390 project write-ups

To ensure precise scientific conclusions from experimental studies requires consideration of the research hypothesis in selecting approaches, procedures and the statistical models to be employed (Zolman, 1999; Kugler, 2002). This indicates that if a scientific hypothesis has not been described or is inappropriately defined then there is the likelihood that data collected may be invalid or unreliable (Romesburg, 1981). It is also imperative that the selection of statistical models and the design of experiments are established concurrently. Specific statistical models come with assumptions that need to be met, to ensure the reliability and validity of results are achieved. These assumptions may include randomized designs, control treatments, large sample sizes, independent testing and so forth. Decisions regarding statistical tests and experimental design should not only be made in conjunction with a research hypothesis but also prior to any data collection. Too often, decisions regarding statistical analyses are made after data collection has been completed (Zolman, 1999). This may result in the misapplication of statistical models by naïve researchers who may not have considered some of the assumptions necessary in their use. A reason for students' tendency to select statistical models post data collection is perhaps attributed to their experiences in undergraduate curricula where statistics courses are predominantly studied separate from their biological courses (Zolman, 1999).

In this study over 90% of the students used statistics to analyse their results. This indicates that most mentors insist on the use of statistics in biological research. The examination of the correct use of statistics utilized by the students was beyond the scope of this particular study. However, students use of randomization, repetition and controls was assessed. The importance of sample size and replication was noted by students as essential in their experimental designs and was highlighted by the majority of students including sample sizes and the replicates numbers in their methods section of their project write-ups. These essential attributes of experimental design have obviously been highlighted throughout students' undergraduate careers and by mentors throughout their BIOL 390 research projects.

Less than half of the students however mentioned randomization and controls in their project write-ups. Of those students who mentioned the use of randomization, very few (<10%) described how they randomized in their experimental designs. This suggests that although they have a conceptual understanding of the necessity of randomization, their ability to apply it to actual research is underdeveloped. Although it is unclear whether students did in fact include randomization and controls in their experimental design but failed to mention it in their methods, the insufficient emphasis of these in their methods indicates that students do not necessarily consider them as essential attributes in experimental design. A lack of consideration of randomization and controls also suggests that students may not have a complete comprehension of the statistical models (which have specific assumptions that include these two elements) they are employing in their research.

It is imperative that students understand why they are conducting experiments and the role that experimental design and statistical tools plays in the scientific process. Experiments are tools used by scientists to test scientific hypotheses through the logical controlling and manipulation of variables in an attempt to shift from ideas of correlation to causation (Cohen and Manion, 1980; McComas, 1996; McPherson, 2001). Reliability of data obtained from experiments forms the basis for claiming that a causation exists (Haig, 1995). Threats to the validity of inferences obtained through experimentation are ruled out when strict consideration is given to the controlling of extraneous influences (Romesburg, 1981; Cowger, 1984). By ruling out these sampling errors one ensures a strength in the inferences obtained from the sample statistic (Cowger, 1984; Hodson, 1998). Thus the careful consideration and implementation of experimental design and statistical tools is crucial in reaching accurate, valid and valuable conclusions.

Students' reasoning and concluding abilities in their BIOL 390 project write-ups

Most students followed a standardized textbook approach to their discussions which focused on the clarifying of facts with little effort in highlighting how facts relate to one another or to other theories. Kosso (2009) describes this as piecemeal empiricism. Although students showed an ability to utilize previous research and knowledge in order to clarify or compare with their results, they lacked the cognitive ability to recognize and detail how the evidence obtained from their research could be incorporated and interconnected into the broader knowledge of science.

In essence, students in their research projects seemed to stop at statistical hypothesis testing which is likely the result of their focusing on statistical hypothesis testing over and above scientific hypothesis testing. The misuse of hypotheses and the misrepresentation of science in laboratory experiences in the undergraduate curriculum often leads students to believing that statistical hypothesis testing constitutes the whole process of science (Guthery *et al*., 2001; Hutto, 2012). As a result, students predominantly operate in the observation stage of scientific inquiry and few develop the skills necessary to engage in inquiry related to the explaining of phenomena through the testing of scientific hypotheses (McPherson, 2001). Statistical hypothesis testing and scientific hypothesis testing are not equivalent. The detection of patterns is a far less complex undertaking than distinguishing between candidate conjectures through considered devised tests in determining the mechanisms underlying patterns in nature.

Many biological sciences focus on the elucidation of patterns and often end up with published work that contain untested scientific hypotheses in their discussions (Romesburg, 1981; Matter and Mannan, 1989). This was not particularly noted in the project discussions of students in BIOL 390. The majority of the students either accepted or rejected statistical hypotheses or predictions in their discussions but did not provide additional evidence to indicate their ability to propose possible scientific hypotheses to be tested in order to explain the mechanisms underlying the observed patterns in their research. Many students concluded their projects with statements such as 'the results were as predicted' but didn't indicate how these results support a particular theoretical idea. It appears as though students consider experiments as conclusive in nature and that theoretical ideas are believed to be accepted in the absence of other theoretical knowledge (Kosso, 2009).

No single test or piece of evidence can confirm or disconfirm a hypothesis (Kosso, 2009). A correspondence between expected and observed results does not necessarily prove a hypothesis to be correct (Lawson, 2000). In reality two or more hypotheses could lead to the same prediction. Equally, a lack of correspondence does not disprove a candidate causal mechanism as this discrepancy may be due to extraneous factors associated with experimental design rather than an incorrect claim (Lawson, 2000). We seldom explain to students that consistency with data and the correspondence of predictions with evidence does not award "truth" status to a scientific hypothesis (Karsai and Kampis, 2010). Consistency with data indicates that the theory or hypothesis may be true, but this may also apply to numerous other theories (Karsai and Kampis, 2010). Conclusions by students that stopped at merely accepting predictions or statistical hypotheses indicates that students may not fully grasp the fact that one confirming piece of evidence is not sufficient to be conclusive evidence that a hypothetical idea is correct.

Students appear to be content to approach their research in an empirical piecemeal manner that follows a single idea from conception to its verification through experimental testing mostly separated from the influence of other theories. However, scientific ideas and practices in science are in fact fundamentally interconnected (Kosso, 2009). To not consider this interconnectedness that links theories and observations and theories to other theories, indicates a lack of understanding of the importance of the structural network of scientific knowledge which is an essential feature of what makes science scientific (Kosso, 2009).

The role of faculty mentors throughout the BIOL 390 research projects

Scientist mentors play a critical role in the success of apprenticeship-type courses. Their role in the choice and designing of research projects as well as the extent to which they explicitly engage students in the nature of science and scientific inquiry determines the extent to which students overcome misconceptions in science (Bell *et al*. 2013).

The majority of the projects offered to students for their BIOL 390 projects were experimental in nature. Reasons for this may include the fact that these particular studies are manageable given the limited time constraints or the fact that they are associated with research that faculty are currently conducting. Given that one of the common misconceptions in the nature of science is that experiments are the only way to sure knowledge in science (Lederman, 1992; McComas, 1996), it is important that this misconception is not reinforced by students conducting only experimental studies. This may be circumvented by mentors engaging students in discussions in the planning stage of their research projects that focus on alternative approaches that could be employed by scientists to test theoretical ideas.

Not only were the majority of projects offered to students experimental but they were also largely replication studies of previous research. Such studies are an essential aspect of science in providing accumulating evidence for the support of theoretical ideas, however they do not allow students the opportunity to creatively generate possible explanations and design authentic research projects. Equally, these studies often focus on the elucidation of patterns, with few projects providing students with the opportunity to employ the hypothetico-deductive approach to science in its entirety, due to the basic questions and methodology already being set by the academic staff member. When considering the provision of research opportunities for students at 3rd year level, faculty need to consider whether they are content on providing projects that identify patterns or whether they desire for students to develop the ability to answer causal questions.

The misuse of statistical and scientific hypotheses and predictions as well as the exclusion of critical elements of experimental design in many of the BIOL 390 students research projects highlights that misconceptions were not confronted by mentors through the research experience. However, it has also been noted that practicing scientists are not exempt from misusing and misrepresenting the scientific process and so long as they incorporate the words 'hypothesis' or 'prediction' they believe they are doing science (McPherson, 2001; Hutto, 2012). It is unclear from this particular study whether misconceptions observed were related to students' misconception or the combination of student and mentors misuse of aspects of the scientific enterprise. However, what is apparent is that future BIOL 390 courses include considerations of these misconceptions identified in this particular study.

Effective mentoring requires epistemological knowledge on how students learn. Many faculty academics hold epistemological beliefs that the way students learn science is to do science and therefore do not consciously embark on explicitly teaching nature of science and scientific inquiry concepts (Bell *et al*., 2003). Scientists who lack pedagogic training are often unaware of the process skills they practice daily in assessing and approaching problems in their personal research (Feldon *et al*., 2010). Through experience they have developed theoretical and conceptual frameworks that allow them to recognize meaningful patterns; effectively organize knowledge and apply these to novel situations. Unfortunately, they are frequently oblivious that novices lack these skills (Coil *et al*., 2010). As individuals acquire expertise they require less conscious examination of the skills and procedures they habitually use in their research (Feldon *et al*., 2010). This can often lead to "step-skipping" behaviour (Koedinger and Anderson, 1990), resulting in omission of key components when communicating their problem solving processes to students. Science educators can help guide mentors by both alerting them to common misconceptions in the scientific enterprise as well as emphasizing the importance of explicit discussion in the areas of the nature of science and scientific inquiry. The provision of guidance for mentors and the incorporation of these features in the planning stages of research projects might assist in overcoming common misconceptions (Bell *et al*., 2003).

Students require explicit instruction on how elements such as hypotheses, predictions and theories fit together and 'how the practice and the standards used by scientists work together in a coherent method' (Kosso, 2009). Mentors must engage students in all aspects of research not only on immediate tasks and procedures. It is essential that students understand the bigger picture of what science is and that they are conscious at every stage in their research projects of where they are operating within the whole process (Bell *et al*., 2003; Proulex 2004). It is equally important that students are made aware of how their work fits into the framework of scientific inquiry. It is also necessary to ensure that mentors agree on what constitutes authentic scientific inquiry. This would entail that mentors proactively follow and mentor students through the course guidelines and expectations.

Concluding remarks and future research

This study provides a descriptive analysis of students' ability to apply conceptual understandings through mentored research experiences. It highlights areas of concern regarding the understanding and use of hypotheses and predictions as well as aspects of experimental design such as randomization and controlling of variables. It is clear that students have gained much in respect to the skills involved in journal article writing, reviewing and assimilating of literature as well as the use of statistical analyses. This study therefore provides evidence supporting the benefits in incorporating research experiences in the undergraduate curriculum. However, the accurate understanding and application of the whole process of science has not been fully realized through these BIOL 390 research projects.

Careful consideration of future projects offered to BIOL 390 students must be undertaken in order to ensure that the misconceptions highlighted in this particular study do not persist. It may be necessary to provide faculty members with guidelines to ensure that they engage students in discussions regarding the nature of science throughout each phase of their research projects. Since these projects were written up in a journal article format it is unclear whether students progressed through the cognitive processes of generating and selecting from alternative explanations with their associated deductive consequences before embarking on their particular investigations. Future BIOL 390 courses may benefit from students, in conjunction with mentors, participating in the construction of a network diagram that provides insight into the knowledge structure in which they are working (Ford, 2000). The construction of this network involves both a conceptual and propositional analysis which assists in identifying links and relationships between different types of knowledge as well as highlighting where and whether the network of knowledge can be extended or simplified (Ford, 2000). The construction of this network diagram also ensures that data statements, particular approaches and methods, details of experimental design as well as the statistical models are selected prior to any data collection.

Future studies on BIOL 390 projects should include pre- and post-questionnaires followed by in-depth interviews with both students and mentors in order to determine student gains through these improved mentored research projects. The combination of these interviews and the construction of knowledge network diagrams alongside experienced science mentors is likely to encourage students to reflect on the relationships between their work and the broader scientific network of knowledge as well as provide them with a better comprehension of how knowledge is generated in science.

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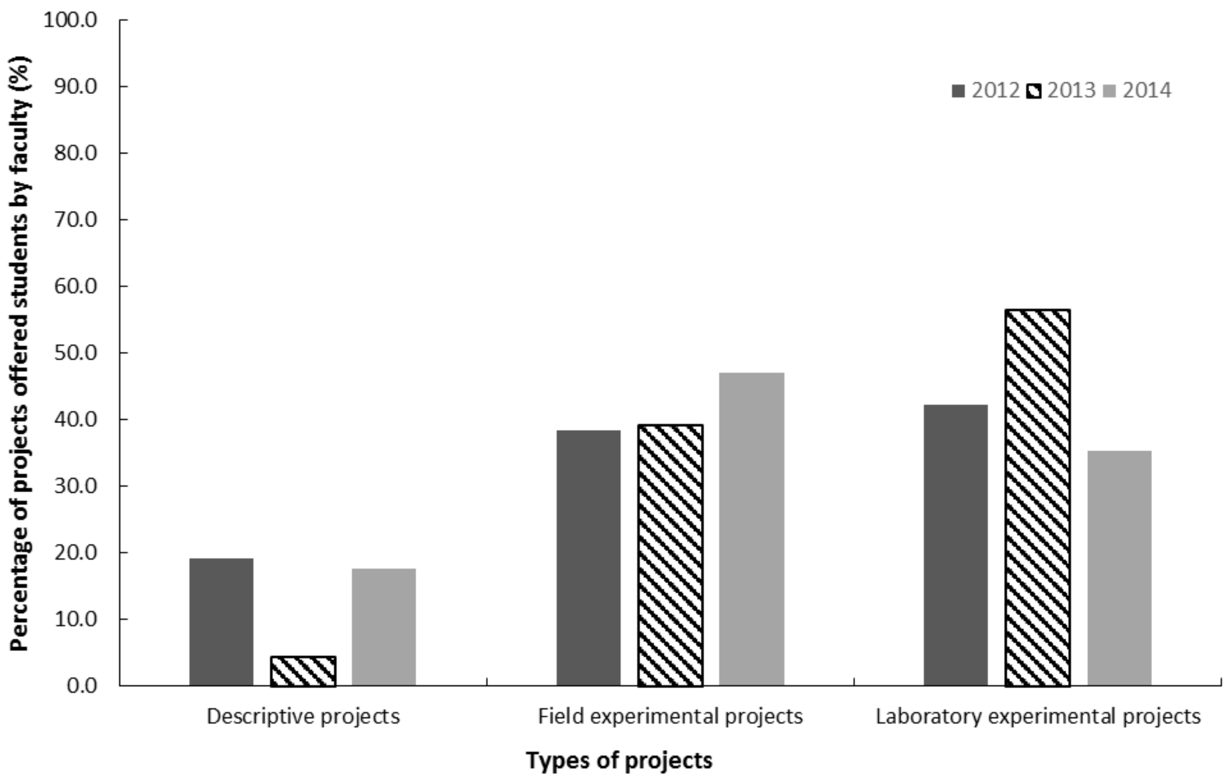

Figure 1: Percentage of 3rd year projects (n = 104) offered to students by faculty falling into three categories from 2012 to 2014.

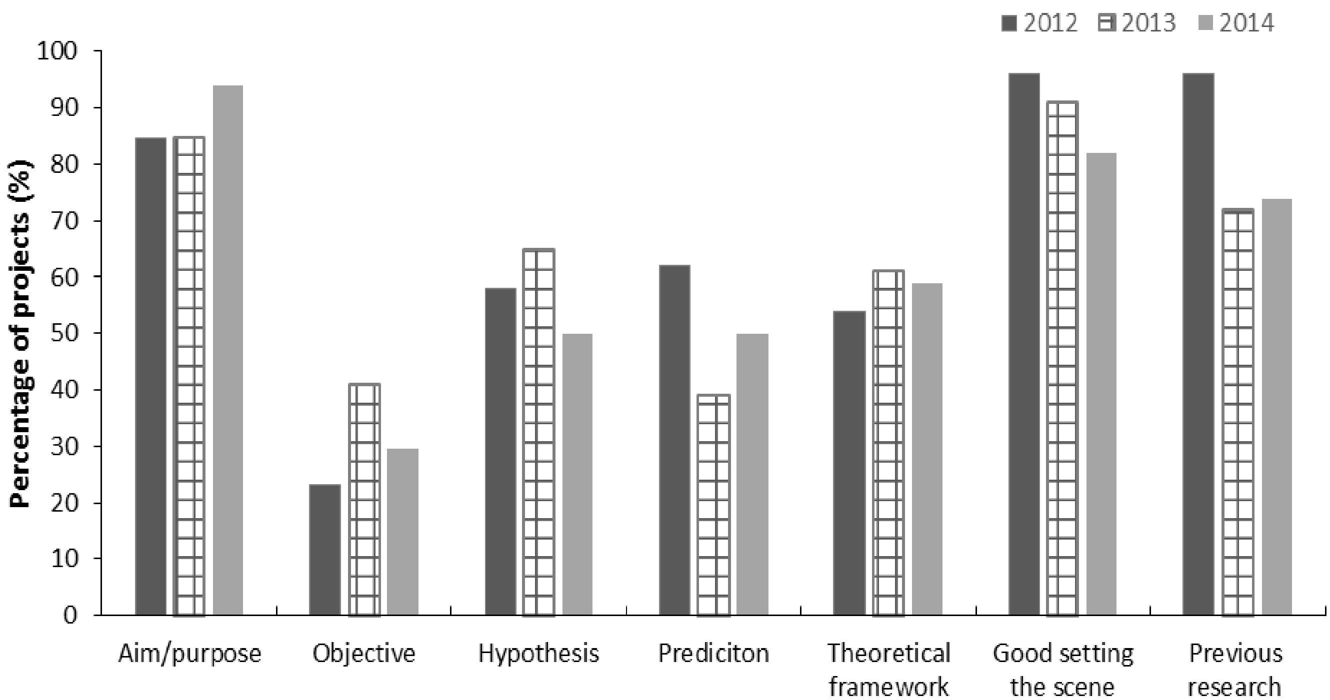

Figure 2: Percentage of BIOL 390 project write-ups from 2012 (n = 26), 2013 (n = 46) and 2014 (n = 34) that contained specific criteria in their Introductions.

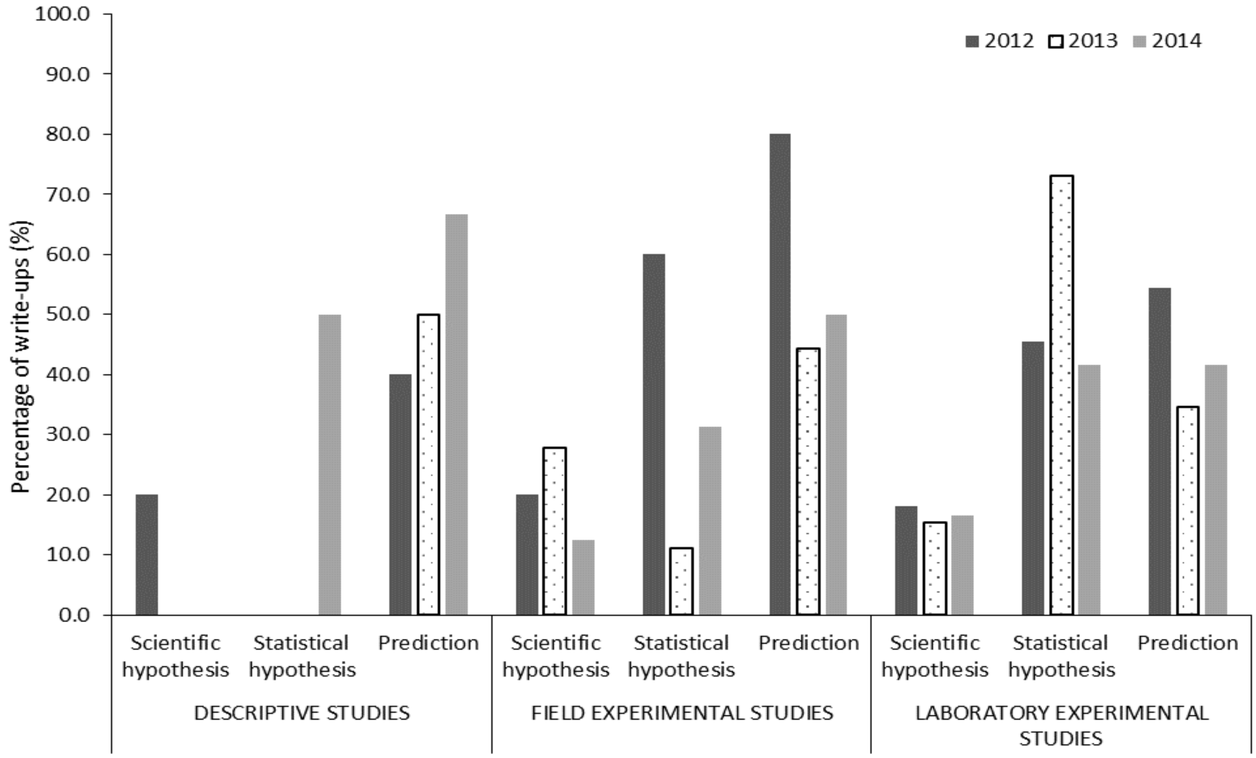

Figure 3: Percentage of BIOL 390 project write-ups containing scientific hypotheses, statistical hypotheses and predictions in each of the three categories of study (descriptive, field experimental and laboratory experimental studies) in 2012 (n = 26), 2013 (n = 46) and 2014 (n = 34).

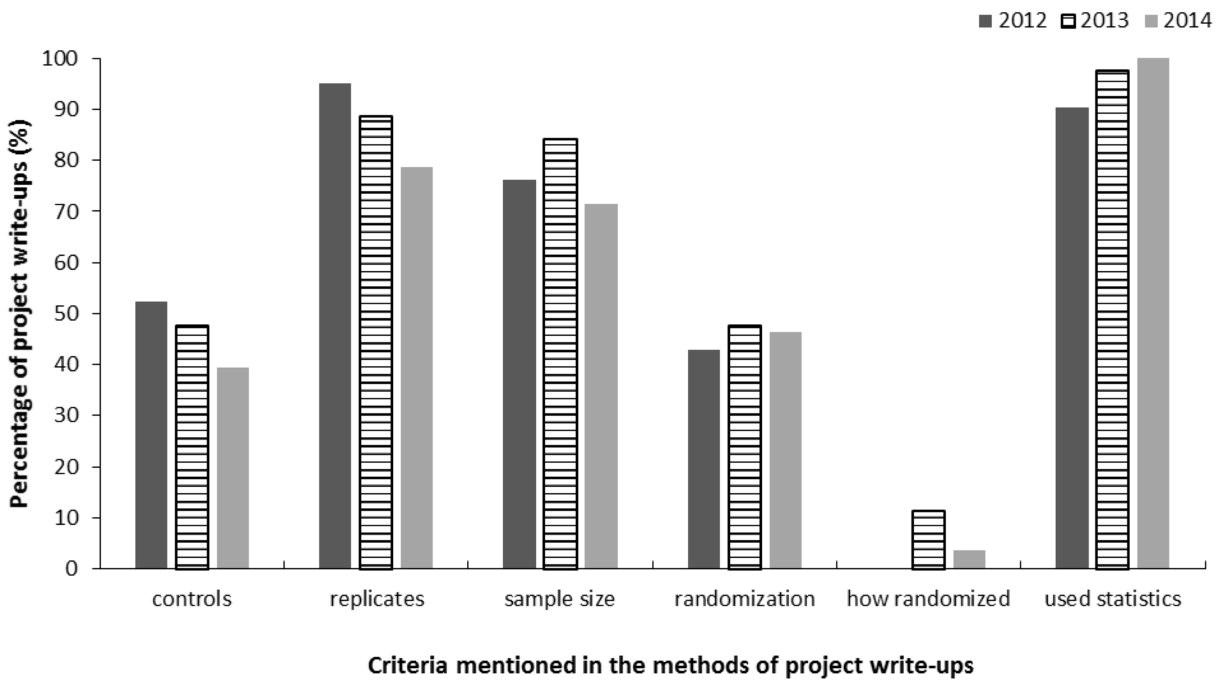

Figure 4: Percentage of BIOL 390 experimental project write-ups from 2012 (n = 21), 2013 (n = 44) and 2014 (n = 28) that contained specific criteria in their Methods.

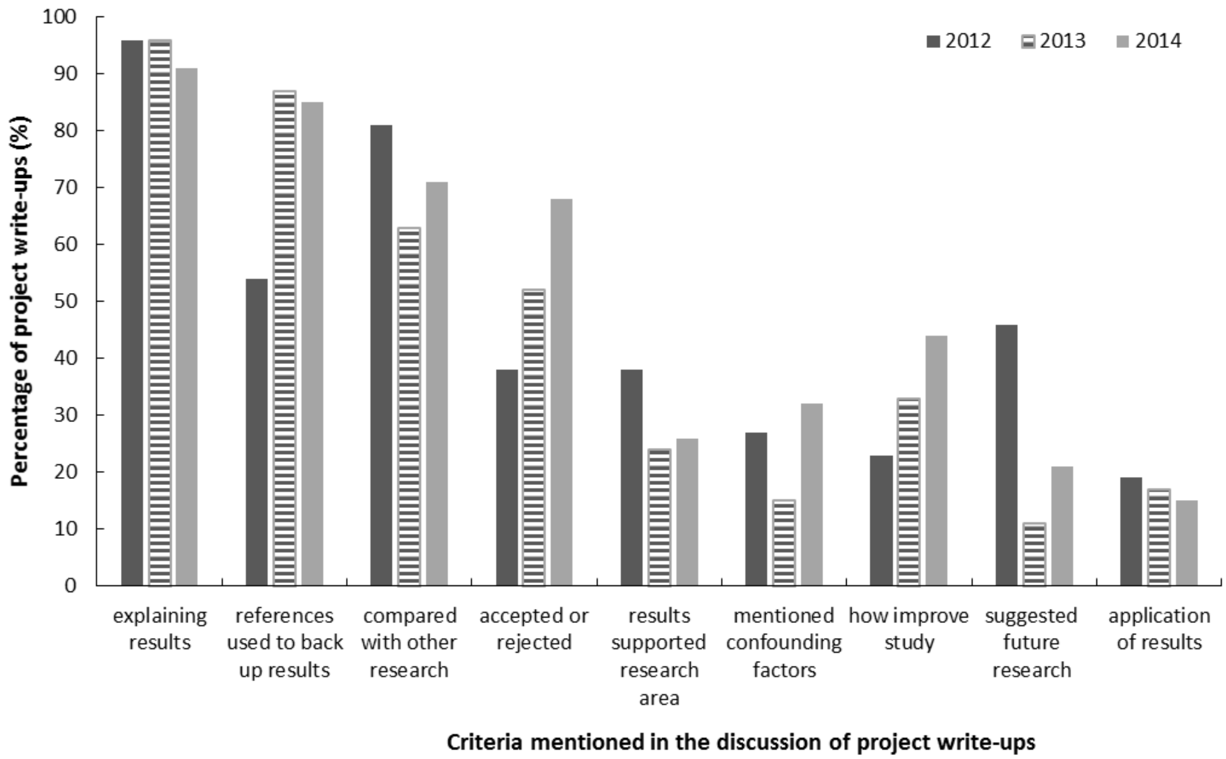

Figure 5: Percentage of BIOL 390 experimental project write-ups from 2012 (n = 21), 2013 (n = 44) and 2014 (n = 28) that contained specific criteria in their discussion and conclusion.

CHAPTER 7

CONCLUSION

The *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2010) is an appeal to transform undergraduate biology curricula in order to better prepare the next generation of scientifically literate citizens for the 21st century. This vision looks to improve biology curricula by seeing transformation from faculty-centered teaching that is predominantly a content-based approach to a more student-centered approach focused on developing core concepts and competencies (AAAS, 2010). In order to achieve this, faculty are required to become reflective facilitators of their instruction. In other words, curricular design requires the careful consideration and articulation of expected learning outcomes and the integrating of these into instruction, planned learning activities and assessments. It has been proposed by Wiggins and McTighe (2005) that a "backward approach" should be implemented in curriculum design whereby assessments guide the planning and implementation of instruction. Assessments should be deliberately designed to determine students' achievement of expected learning outcomes as well as to inform future instruction.

Scientific literacy requires students to be proficient both in the Nature of Science and Scientific Inquiry. A large volume of research has shown that students have numerous misconceptions about NOS and SI. (Lederman, 1999; Bell *et al*., 2000; Lederman *et al*., 2002; Schwartz and Lederman, 2008). These misconceptions include views such as scientific knowledge being certain and objective which is usually obtained through a universal scientific method. Confusions between the terms empirical evidence and experimental evidence stimulates misconceptions that the only route to scientific knowledge is through experimentation (McComas, 1996; Lederman *et al*., 2002; Bednekoff, 2003).

Research in the Nature of Scientific Inquiry have highlighted misconceptions that are prevalent in scientific inquiry. Some of the misconceptions that have been highlighted include the view that all scientific inquiry requires hypotheses and the use of a single objective scientific method ensures that scientists always get the same results if investigations are repeated (Schwartz and Lederman, 2008; Bartos and Lederman, 2014; Lederman *et al*., 2014b).

This research thesis has identified that students, teachers and scientists have varied views regarding the basic concepts of the scientific process. Much of the research on NOS and SI has been conducted in America. Very little research on the Nature of Science or Scientific Inquiry has been conducted in the South African context, particularly at the tertiary education level. Engaging students in meaningful research experiences in these contexts is challenging, particularly when students enter tertiary education with diverse skill sets and cultural backgrounds. Many students entering South African tertiary institutions have never had the privilege of experiencing scientific investigations in any form. They come with varied views of science which have developed from experiences, different cultural beliefs and the inadequate instruction at school level. Many students entering South African tertiary institutions are English-second language learners who struggle with complex terminology used in science. As a result of these factors, and the high enrolment numbers, introductory courses usually reflect that of traditional-style lecturing and “cookbook” laboratory experiences that provide students opportunities to learn basic laboratory techniques, data collection, interpretations and presentation of results. These are designed to ‘acclimatize’ students to scientific investigation.

Defining of broader questions, developing of hypotheses, and designing of investigations are mostly carried out by faculty and laid out clearly in coursework laboratory manuals.

In this thesis I set out to determine if students attending a South African University (University of KwaZulu-Natal) exhibit similar struggles with basic concepts of the process of science. In particular I focused on what conceptions students gained throughout their undergraduate careers in terms of the conceptualizing of theory, statistical inference, hypothesis setting and testing, the appropriate use of predictions, and essential concepts of experimental design such as replication and randomization. Finally, students' ability to draw together and link research into the broader theoretical context was also analysed at the third year level.

The generation of research hypotheses and predictions, as well as the design of investigations requires higher-order cognitive skills. Experimental design or the design of investigations is integrally linked to clear directive hypotheses and the choice of statistical analyses. The way in which an investigation is conducted, and the use of repetition and randomization is rooted in the research hypothesis and the statistical model selected prior to data collection. Data collected arbitrarily will result in inaccurate and invalid measurements and meaningless inferences (Lennon, 2011; Zolman, 1999). A clear conceptual and procedural comprehension of these concepts in scientific inquiry are necessary for students to operate effectively in scientific research. Appropriate definitions and application of concepts such as hypotheses, predictions, theory, repetition and randomization are good indicators of students' comprehension of the process of science.

I found common misconceptions across two campuses of the University of KwaZulu-Natal for most of these concepts, with very little improvement shown as students progressed from first year to third year level (Chapter 3). Analyses of faculty conceptions of research hypotheses, alternative hypotheses, replication and randomization suggests that students understanding of these concepts at the end of their third year is largely biased towards those of faculty rather than textbook introductions or course manuals (Chapter 2 and Chapter 5). Only 20% of faculty, and less than 6% of third year students, describe research hypotheses as explanations. However, both acknowledge research hypotheses to be testable. Both faculty and third year students largely associate alternative hypotheses with statistical hypotheses rather than alternative explanations to phenomena. Responses to questions regarding replication and sample size elicited varying answers for both faculty and third year students. Faculty responses seemed to be associated with differences in their disciplinary research. Interestingly, both faculty responses and third year responses showed patterns in their description of sample size or replication. Faculty and third year student responses specifically stated ideas such as: 3-5 replicates or 5-10% of the population with others responses referring to dependence on the amount of variability in the study population. Both faculty and third year students regard randomization as a necessity to reduce bias.

Assessments have the potential to transform undergraduate biology curricula. This occurs when assessments are viewed not only as tools to measure students' achievement of learning goals, but also as a means of informing instruction and to help guide decisions about the course. It is necessary that faculty apply a variety of assessment tools that not only measure students' ability to master facts but also conceptual understanding and the attainment of competencies. The identification of appropriate assessment tools also requires careful consideration of students backgrounds associated with their beliefs, experiences and language proficiency.

Critical analysis of assessments is necessary to ensure that they are adequately assessing what they were designed to test. The Blooming Biology Tool is an instrument designed to help faculty determine whether their assessments are testing both lower-order and higher-order cognitive skills. An examination of the assessments provided to students in an introductory course at the University of KwaZulu-Natal indicate that there is a bias towards testing lower-order cognitive skills (Chapter 4).

The Vision and Change document also calls for the design of research experiences that more accurately reflect authentic research (AAAS, 2010). Students at UKZN in their final year of undergraduate study can participate in a research project that is mentored by faculty. This thesis aimed to assess students' ability to conduct authentic research and apply conceptual understandings of Scientific Inquiry. Despite answering this call to provide authentic research experiences, results showed that third year students' final write-ups still held commonly found misconceptions (Chapter 6). Many students used predictions inappropriately, and a large majority of students failed to incorporate critical aspects such as randomization and controls into their experimental designs. There are two possible causes for the perpetuation of these misconceptions. Firstly, this may be related to some faculty possessing misconceptions themselves. Secondly, a lack of pedagogical training that enables them to engage students in explicit-reflective discussions throughout the research project. Most mentors appear to focus on developing students' content knowledge in the field of study rather than providing explicit mentoring on the process of science, and the development of the nature of scientific knowledge.

Limitations of study

The chapter focusing on first and second year students' conceptions of experimental design used an existing questionnaire provided by an American source. This may have shown bias against our South African English-second language learners.

Unfortunately, the questionnaire that was sent to all academic staff in the School of Agriculture, Earth and Environmental Sciences and the School of Life Sciences on both the Pietermaritzburg and Westville Campuses had only a 20% return rate. This may have resulted in biased results towards views from faculty from specific disciplines and may not have given a holistic view of the conceptions of faculty staff at the University of KwaZulu-Natal.

Despite this thesis' ability to highlight students' conceptual understandings regarding various aspects of the process of science it remains largely a descriptive study. Pre- and post-tests have been used by researchers to determine student gains across courses as well as student interviews which are capable of more in-depth examination of students' perceptions. Due to not being formally involved in the design phase of courses in the curriculum or the running and facilitation of these particular courses, I was unable to implement some of these evaluative strategies. However, the results of this study may be useful for future instructional guidance, the improvement in outlining learning outcomes and the design, implementation and assessing of reform strategies that concentrate on specific misconceptions or difficulties that undergraduate student possess at the University of KwaZulu-Natal.

Future research

Future research may include the implementation and assessment using instruments such as the Views about Scientific Inquiry (VASI) questionnaire and Views of Nature of Science Questionnaire (VNOS) designed by specialists in these fields of study and which have been globally used to assess students' conceptions. Future research should also include the provision of mentor training and pre- and post- tests to determine the influence of mentor's explicit-reflective approach to mentoring students through third year authentic research experiences.

Recommendations

Suggestions for reform include the need for faculty staff to engage up to date pedagogical research on how science should be taught. There has been a global trend in science education in the generation and distribution of instruments that document agreed-upon collections of learning outcomes for undergraduate courses, as well as theoretical frameworks, that can help faculty in the design and implementation of course curricula that concentrates on developing core concepts and competencies. We also recommend a recognition to move away from predominantly knowledge content transfer alone towards including skills transfer. Training is necessary for faculty staff in terms of what misconceptions exist associated with hypotheses, predictions and experimental design and a co-operation between faculty members both within and across campuses of the University of KwaZulu-Natal in determining agreed upon conceptualizations of these aspects of the process of science. Lastly, we recommend curriculum reform to include the provision of clear measurable learning outcomes for undergraduate courses that require the integral aligning of instruction and assessments that ensure students achieve these goals. Lastly, we also recommend analyzing assessment types used at UKZN in order to ensure that sufficient higher-order cognitive skills are assessed, rather than predominantly lower-order cognitive skills. These will hopefully ensure that students not only develop conceptual understandings of portions of the scientific process but also become reflective cognitive thinkers of the scientific process as a whole.

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