Grade 12 students' understanding of adaptation, before and after learning about natural selection.

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DECLARATION

I submit this dissertation in fulfilment of the requirements for the degree of Master of Science at the University of the Witwatersrand. I declare that, apart from the assistance acknowledged, this dissertation is my own unaided work. All sources that I have used or quoted have been acknowledged by means of complete citation and referencing. I further declare that I have not submitted this report for any other degree or examination at any other university.

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1 May 2019

ABSTRACT

Adaptation is a concept frequently mentioned in the South African Natural Sciences and Life Sciences curricula, and an important part of evolutionary theory. Evolutionary theory provides a vital explanatory framework for many biological topics and is a principle element in the development of students' scientific literacy – the ability to apply correct scientific knowledge in our everyday lives, or in careers, to improve the quality of lives. Because evolutionary theory underpins and supports an understanding of most biological phenomena and processes, knowledge of evolution-related concepts, like adaptation, is vital for scholars and members of the public if they are to be considered scientifically literate.

This dissertation describes the nature and extent of the ideas held by 90 South African Grade 12 students' from three schools, in terms of their understanding of adaptation and natural selection before and after learning about evolution in Grade 12. Two data collection strategies were used to determine the extent of students' understanding. Written diagnostic activities were completed by students before and after being taught natural selection. Each diagnostic activity had four questions: two were comprehension-level questions on Bloom's taxonomy, requiring students to explain *adaptation* and *natural selection*. The last two questions were application-level questions on Bloom's taxonomy: these scenario-based questions described previously unseen situations and required students to explain how the situations occurred. Students were given equivalent versions of the scenario-based questions before and after instruction. All 16 students from one of the schools were then interviewed after being taught the topic, to probe their answers from the written activities. Open coding and frequency counts were used to analyse open-ended answers from the diagnostic activity and the transcribed interviews, and t-tests and the McNemar variation of the chi square test were employed to check if pre- and post-instruction differences were statistically significant.

The study had five objectives. The first was to establish the nature and extent of scientific concepts in students' answers. Generally, students had a poor understanding of adaptation and natural selection before evolution instruction. In their explanations of *adaptation* before instruction on natural selection students averaged 1.33 correct statements out of the six key concepts considered essential for a correct answer, and only 0.14 correct ideas (on average) when explaining *natural selection*. In the scenario-based questions, students averaged 1.22 correct statements out of the required eight to explain colour changes in peppered moths, and 0.57 correct statements (on average) for a question about changing ear size in elephants, showing that the context of questions had an impact on students' answers. Statistically significant improvements were found for three of the four diagnostic activity questions after instruction. Improvement in students' explanations of *adaptation* were small, increasing from 1.33 to 1.44 ($p = 0.28$), while the average score for the *natural selection* explanations, increased significantly from 0.14 to 0.76 ($p = 0.004 \times 10^{-5}$). For the equivalent versions of the scenario-based questions, students averaged about two correct statements (of the required eight) for both a question on colour change in fruit chafer beetles and a scenario in which seals developed the capacity to stay longer under water: both questions showing statistically significant improvement ($p = 0.003 \times 10^{-3}$; $p = 0.001 \times 10^{-6}$ respectively).

The second objective was to identify the concepts that were missing in students' answers to the diagnostic activity. Many of the key concepts considered to be essential for correct answers were missing from students' explanations. Prior to instruction, more than 80% of students missed at least four of the six correct statements in their explanations of *adaptation*, more than 80% of the students missed all six of the correct statements in their explanations of *natural selection* (five of which were missed by 99% of students), and five of the eight correct ideas were missing in 80% or more of students' answers for both scenario-based questions. After instruction, statistically significant decreases were found in the frequency of missing concepts. For the *adaptation* explanation three of the six statements showed statistically significant reductions in their absence, whilst three statements for the *natural selection* explanation, and six of the eight statements for the scenario-based questions showed statistically significant reductions. However, the number of missing concepts remained high. More than 80% of

students were still missing at least three of the six correct statements about *adaptation;* five of the six correct statements were missed by 80% or more students for the *natural selection* question; and two of the eight were missed by 80% or more in the two scenario-based questions.

The third objective was to determine the nature and extent of students’ misconceptions in their responses to the pre- and post-diagnostic activity questions. Students’ misconceptions about adaptation and natural selection were frequent and diverse. Of the thirteen most commonly mentioned misconceptions, the idea that *adaptation is caused by environmental change* led the list across all four questions (mentioned 169 times before instruction; 136 after), followed by the idea that *adaptations are caused by an organism’s need for them in order to survive* (mentioned 152 times across all four questions before instruction, and 132 after). Six of the thirteen most commonly mentioned misconceptions showed statistically significant reductions after instruction.

The fourth objective was to determine to what extent students used ‘alternative frameworks’ (scientifically incorrect explanatory frameworks made up of multiple interconnected misconceptions, that seem to influence the way students think about adaptation). While four alternative frameworks noted in the literature were found in students’ answers ('evolution on demand', 'survival of the fittest', Lamarckism, and essentialism), the 'evolution on demand' alternative framework was the most common in students’ answers, both before and after instruction. However, a statistically significant decrease was seen in the number of students using the alternative framework after instruction (49% of students used it before, and only 30% after: $p = 0.03$). The six misconceptions to do with the 'evolution on demand' alternative framework were also the top six most frequently mentioned misconceptions in students’ responses to the diagnostic activities, both before and after instruction. The number of students who used the 'survival of the fittest' alternative framework showed an increase of 10% in frequency after instruction, though this did not prove to be statistically significant (17% before, 27% after, $p = 0.09$). Very few students used Lamarckism (only ten) or essentialism (only three).

The final objective was to investigate students’ use of teleological and anthropomorphic thinking in their answers to the diagnostic activities. Teleology (attributing evolutionary changes to need or purpose) was found more often in students’ answers than anthropomorphism (ascribing human behaviours or characteristics to animals or inanimate objects). A little more than a third of students used both teleology and anthropomorphism in their explanations of *adaptation*, and about a quarter in their responses to the scenario-based questions. Statistically significant decreases were seen in students’ use of teleology when comparing students’ answers before and after instruction about natural selection. Students’ use of anthropomorphism showed a statistically significant decrease in their explanations of adaptation, but not in their responses to the scenario-based questions. This suggests that teaching about natural selection can decrease students’ use of these two unscientific ways of thinking in their explanations of adaptation, even though the two types of wording were not specifically dealt with in class.

This research could be of value to teachers in the following ways. Firstly, it highlights the inextricable link between adaptation and natural selection and the need to teach both topics simultaneously. Secondly, it separates the definition of adaptation and natural selection into a set of key concepts for students to be aware of. Thirdly, it points out common misconceptions (especially those related to the 'evolution on demand' alternative framework) that teachers can aim to confront while teaching adaptation in class. Finally, it points out the potential pitfalls of using certain types of figurative language (especially teleology and anthropomorphism) and how they can inhibit, rather than promote, understanding.

DEDICATION

This work is dedicated to:

To my dear wife for her love, patience and support.

To Rachel, Eoin and Lydia for their understanding and patience as I worked on this project.

To my students past, present and future. I hope you develop a love for the created world and all its creatures and contribute to preserving and conserving it.

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Background to, and rationale for, the study

The concept of ‘adaptation’ is a recurring topic in the Curriculum and Assessment Policy Statement for both Natural Sciences and Life Sciences in South Africa. Adaptation is listed as a topic to be taught in Grade 7, 8, 10, 11, and 12, with particular emphasis on the topic in Grade 8. There are many unscientific ideas among students about the topic of adaptation worldwide (for example, Engel Clough & Wood-Robinson, 1985a; Jungwirth, 1975) which is driven by a lack of understanding of the mechanism of adaptation, natural selection. This project identified the scientific and unscientific ideas about adaptation held by 92 Grade 12 students from three schools in Johannesburg, before and after learning about natural selection.

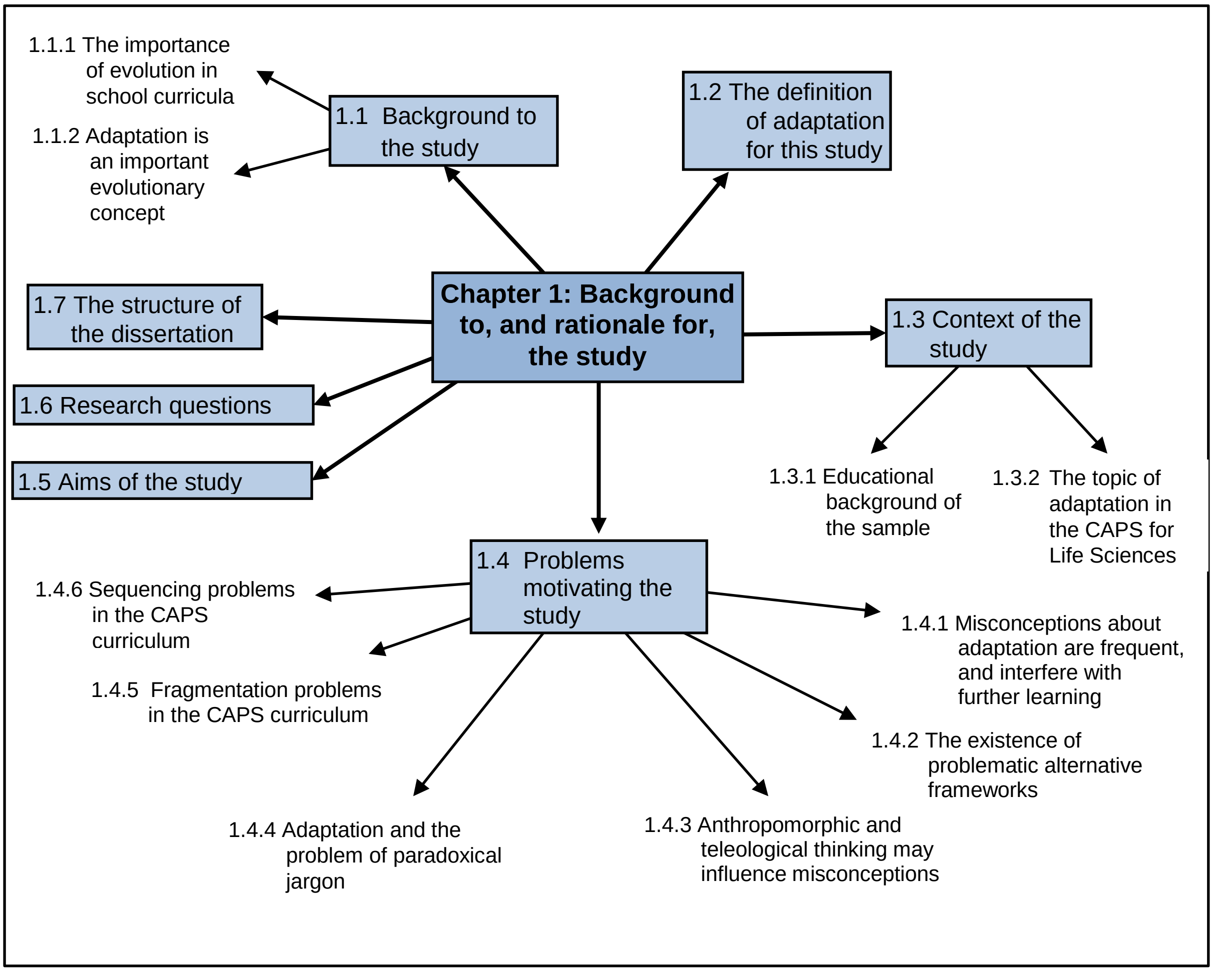

Figure 1: Structure of Chapter 1

1.1 BACKGROUND TO THE STUDY

This study was conducted in the field of science education generally, and evolution education specifically. This section emphasises the fact that the topic of adaptation is not an isolated topic to be taught on its own, but one that is inseparably tied to the broader topic of evolution.

1.1.1 The importance of evolution in school curricula

Adaptation has been described as “one of the original ideas in evolutionary studies” and a “core concept” by Bock (1980, p. 217), a “phenomenon of pervasive importance in biology” by Williams (1966, p. 5) and a “fundamental concept” by Ghiselin (1966, 147). However, the concept of adaptation is not an isolated topic in biology, but an integral part of the broader topic of evolution. Thus, to comprehend the importance of adaptation in biology, one must first understand the importance of evolution in biology (Futuyma, 2009).

Evolution by natural selection is considered by many scientists to be one of the greatest ideas in the history of human thought (Futuyma, 2009). The National Academy of the Sciences (2008, p. xi) argues that “Evolutionary biology has been and continues to be a cornerstone of modern sciences”. Evolution is important to biology for four reasons. Firstly, evolution provides an essential “explanatory framework” (Anderson, Fisher, & Norman, 2002), apart from which nothing in biology would make sense (Dobzhansky, 1973). Secondly, evolution is a unifying theme (American Association for the Advancement of Science, 2006; McComas, 1994; Nehm, Poole, Lyford, Hoskins, Carruth, Ewers, Colberg, 2009; Rutledge & Mitchell, 2002) or “the central organising principle” in biology (National Academy of the Sciences working group on teaching evolution, 1998, p. 3), capable of explaining “disparate facts and observations from widely different fields” (Lazcano & Peretó, 2010, p. 664) under one coherent banner of understanding. Evolution is the common thread that unites diverse scientific fields like astronomy, palaeontology, anthropology and biology (Dobzhansky, 1973; National Academy of the Sciences, 2008). Evolution is also a common theme uniting the many fields of biology, like genetics, embryology, comparative anatomy, biochemistry, and molecular biology (National Academy of the Sciences, 2008; Webb, 2010). It is capable of bringing together many unrelated facts that would otherwise be reduced to a “pile of sundry facts […] making no meaningful picture as a whole” (Dobzhansky, 1973, p. 129). Thirdly, an understanding of evolution has led to many technological advances that have been used to improve human life. The technology of artificial selection has been used for centuries, even before evolution was fully understood (Bull & Wichman, 2001). Knowledge of artificial selection is still being used, alongside gene editing-technologies, to modify crops to be resistant to pathogens and harsh environmental conditions (Campbell, Reece, Urry, Cain, Wasserman, Minorsky, Jackson, 2015). Finally, evolution is an important problem-solving tool. Bull and Wichman (2001) point out that health researchers have used Darwin’s theory of ‘descent by modification’ to identify the origins of disease-causing pathogens like drug-resistant tuberculosis and drug-resistant HIV.

The importance of evolution as an explanatory framework, as a unifying concept, as a means of technological advancement, and as a problem-solving tool in biology explains why scientific organisations (such as the Academy of Sciences for the Developing World, 2006) and educational organisations (such as the Association of Science Teacher Education, 2016) have called for evolution to be taught in schools. Teaching biology “without explaining evolution deprives students of a powerful concept that brings great order and coherence to our understanding of life” (National Academy of the Sciences working group on teaching evolution, 1998, p. 3). It is for this reason that evolution has been, and is increasingly becoming, an important part of biology syllabi around the world (Miller et al., 2016; Pazza, Pierre, & Kavalco, 2010; Rutledge & Mitchell, 2002; Schilders, Sloep, Peled, & Boersma, 2009), including in South Africa (Dempster & Hugo, 2006). Evidence of this can be seen in the fact that evolution now constitutes 22% of the Grade 12 Life Sciences syllabus in South Africa, when prior to 2008 it was not mentioned at all in the Grade 12 syllabus (Stears, Clément, James, & Dempster, 2016).

Scientific literacy in school-going students is the broad objective of science curricula globally (McComas, 1994; National Academy of the Sciences, 2008; National Science Teachers Association, 2013), including in South African schools (Dempster & Hugo, 2006; Department of Basic Education, 2011a). Scientific literacy is what the general public should know about science that will enable them to read, think, write, and talk about biological investigations, processes and concepts so as to live more effectively in the natural world (De Boer, 2000; Department of Basic Education, 2011a). Evolution is an important part of scientific literacy, so important that The Oklahoma Academy of Science (2007, n.p.) argues that:

> “A high school graduate who does not understand evolution is not prepared for college or for life in a technologically advanced world, in which the role of biology and biotechnology will continue to grow”.

The National Academy of the Sciences (2008, p. 58) contends that scientific literacy is essential for future employment in high profile, high-paying jobs in the sciences, as such employment increasingly requires an understanding of the “core concepts, applications and implications of science”.

1.1.2 Adaptation is an important evolutionary concept

The concept of ‘adaptation’ is an important part of evolutionary theory. This is evident in the significance given to it in the two founding ideas of Darwin’s theory of evolution (Bock, 1980). The first of Darwin’s history-shaping ideas is ‘descent by modification’. Descent by modification is the idea that new species can develop from “ancestral forms through the gradual accumulation of adaptations to a different environment” (Campbell et al., 2015, p. 509). Campbell et al. (2015) argue that ‘descent by modification’ captures the unity in the family history and common ancestry of all organisms, and their diverse modifications, as species branched out from common ancestors. Darwin’s second idea, something renowned evolutionary biologist Futuyma calls “the greatest idea in the history of human thought” (Futuyma, 2009, p. 6), is natural selection. Natural selection is the explanation for the mechanism by which evolution occurs as certain organisms with characteristics that improve survival and reproduction pass their heritable traits on to the next generation more successfully than those without those ‘favourable’ characteristics, causing both genetic and phenotypic changes in a population over time. Natural selection results in the development of new adaptations as populations of organisms become more adapted to their environment over time (Campbell et al., 2015; Futuyma, 2009). Therefore, the concept of adaptation is inextricably linked to that of evolution (Campbell et al., 2015; Kelemen, Emmons, Seston Schillaci, & Ganea, 2014).

1.2 THE DEFINITION OF ADAPTATION FOR THIS STUDY

The aim of this study was to identify the ideas held by a sample of Grade 12 students about biological adaptation, both before and after the teaching of natural selection. In order to separate the scientific ideas from those that are unscientific, a thorough explanation of what the scientific understanding of adaptation is needs to be established. Before defining adaptation, the closely-related concept of ‘fitness’ is first defined. Fitness refers to the reproductive success of an organism in passing a favourable genotype on to its offspring so that the favourable genotype becomes statistically more frequent in the population over time (Gregory, 2009; van Dijk & Reydon, 2010). Ashelford (2002) and Ghiselin (1966) show that the definition of adaptation is dependent on the context (scientific or everyday) in which it is used, so a definition for adaptation is not easy to find. Definitions differ even within science (Lucas, 1971), where ‘biological adaptation’ has two different meanings, namely the ‘process’ and the ‘product’ (Gregory, 2009; Levine & Miller, 1994; West, El Mouden, & Gardner, 2011), discussed further in section 2.3.1 of Chapter 2. A suitable definition must include both facets. For the purposes of this study, adaptation is defined as a characteristic of an organism that increases it’s fitness, or the process by which populations of organisms increase in fitness relative to their environment (Levine & Miller, 1994).

1.3 CONTEXT OF THE STUDY

In order to understand the context of this study it is important to understand the educational history of the students involved in the study. Data was gathered from two different cohorts of students over two different years. The two groups followed two different curricula in the Senior Phase of their schooling, one group learning about natural selection in the Senior Phase and the other not. Students who have been systematically taught about evolution by natural selection from early on in their schooling are more likely to have a coherent scientific mental framework to account for the presence of adaptations in living organisms, as shown by Kelemen, et al. (2014) and Legare, Lane, & Evans (2013). Those who have not been exposed to the topic, or who have been exposed to evolutionary topics only once they reach high school, are less likely to be able to give a scientific explanation for adaptation because, “they have spent more than a decade of their lives reasoning about biological phenomena in explicitly non-evolutionary terms” (Shtulman, Neal, & Lindquist, 2016, p. 2).

1.3.1 History of curriculum changes in South Africa over the last 20 years

Over the past twenty years, three major curriculum changes have been made at the General Education and Training level (Grades 0 – 9) in South African schools. The first curriculum was called Curriculum 2005 and did not include natural selection as a topic. Curriculum 2005 had many problems and so another curriculum, known as the Revised National Curriculum Statement (RNCS), was introduced progressively by phase from 2004. Natural selection was included in the Senior Phase of the RNCS. The curriculum was revised again, starting in 2012, when the Curriculum Assessment Policy Statement (CAPS) was introduced. Natural selection was removed from the GET level altogether. Of the three curricula mentioned in the preceding sentences, the last two (RNCS and the CAPS) are applicable to my study.

The RNCS Natural Sciences curriculum

The prescribed content of the Senior Phase Natural Sciences RNCS curriculum was specified by phase and not by grade. This left schools open to choose the Senior Phase grade in which they would cover the prescribed topics. It is likely that teachers followed the order of content provided by the textbooks they used. Teachers tend to rely on textbooks to help manage their lessons because it helps with the planning and co-ordination of lessons (Hutchinson & Torres, 1994). Because different textbooks covered the topics of adaptation and natural selection in different grades in the Senior Phase, different schools are likely to have covered the topics in different grades between Grade 7 and Grade 9, based on the location of the content in the textbooks used at the school. This is important because the students in this study were from a variety of primary schools and may or may not have learned about natural selection. The topics of adaptation and natural selection in the Senior Phase of the RNCS Natural Sciences curriculum are illustrated in Table 1.

Table 1: Senior Phase Natural Sciences evolution-related content of the Revised National Curriculum Statement (Department of Education, 2002)

Revised National Curriculum Statement	
Grades 7 - 9.	- All organisms have adaptations for survival in their habitats (such as adaptations for maintaining their water balance, obtaining and eating the kind of food they need, reproduction, protection or escape from predators). (p. 64) - Natural selection kills those individuals of a species which lack the characteristics that would have enabled them to survive and reproduce successfully in their environment. Individuals which have characteristics suited to the environment reproduce successfully and some of their offspring carry the successful characteristics. Natural selection is accelerated when the environment changes; this can lead to the extinction of species. (p. 64)

CAPS Natural Sciences curriculum

The CAPS Natural Sciences curriculum contained three important changes. Firstly, the content was prescribed by grade and not by phase as with the RNCS. Secondly, the topic of **natural selection** was removed in the CAPS Natural Sciences curriculum and is now only found in the Grade 12 Life Sciences curriculum. Thirdly, the topic of adaptation is given more of a focus (more detail) in Grade 7 and 8 and does not appear in the Grade 9 syllabus at all (see Table 2).

Table 2: Evolution-related content of the Senior Phase of the Natural Sciences Curriculum and Assessment Policy Statement (Department of Basic Education, 2011a)

Grade	Curriculum and Assessment Policy Statement
7	• "living things are suited (adapted) to the environment in which they live, such as fish have fins to move easily through water" (p. 17) • "flowers have special adaptations to promote pollination, such as large colourful petals, scent and sweet nectar to attract insects and birds" (p. 19) • survival of individual organisms and populations depends on its ability to cope with changes (adaptation) in its habitat (the place where an organism lives) or in the ecosystem (p. 36)
8	• "adaptation is the change in the structural, functional and behavioural characteristics of an organism". • "adaptation allows the organism to survive as it adapts to changing conditions within the environment". • "organisms that are unable to adapt to changes within the environment die out (become extinct)" (p. 38)

The effect of the curriculum changes on the sample in this study

Data for this study was collected from a cohort of Grade 12s in 2016 and another cohort of Grade 12s in 2017. The 2016 cohort experienced the curriculum change from the RNCS to the CAPS document when moving from Grade 9 (in 2013) into Grade 10 (in 2014), as illustrated by Table 3. This cohort completed the Senior Phase of the Natural Sciences curriculum on the RNCS and can be expected to have learned about natural selection while in this phase. The 2017 cohort experienced the curriculum change between Grade 8 (2013) and Grade 9 (2014), as illustrated by Table 3. Some students in this cohort would have learned about natural selection in Grade 7 and 8, while others would not have learned about natural selection at all, because schools that intended doing natural selection in Grade 9 would not have had the opportunity because when this group reached Grade 9 they had to start on the new

CAPS curriculum that excluded natural selection. Thus, the students from whom data was collected might not all have learned about natural selection prior to their exposure to it in Grade 12.

Table 3: The different curricula followed by the two groups involved in the study

	GET Foundation Phase			GET Intermediate Phase			GET Senior Phase			FET Life Sciences		
Year	**Gr. 1**	**Gr. 2**	**Gr. 3**	**Gr. 4**	**Gr. 5**	**Gr. 6**	**Gr. 7**	**Gr. 8**	**Gr. 9**	**Gr. 10**	**Gr. 11**	**Gr. 12**
2005	🟪 RNCS	RNCS	RNCS	RNCS	RNCS	RNCS	C2005	C2005	C2005	Transition	Transition	Transition
2006	🟩 RNCS	🟪 RNCS	RNCS	RNCS	RNCS	RNCS	RNCS	C2005	C2005	NCS	Transition	Transition
2007	RNCS	🟩 RNCS	🟪 RNCS	RNCS	RNCS	RNCS	RNCS	RNCS	C2005	NCS	NCS	Transition
2008	RNCS	RNCS	🟩 RNCS	🟪 RNCS	RNCS	RNCS	RNCS	RNCS	RNCS	NCS	NCS	NCS
2009	RNCS	RNCS	RNCS	🟩 RNCS	🟪 RNCS	RNCS	RNCS	RNCS	RNCS	NCS	NCS	NCS
2010	RNCS	RNCS	RNCS	RNCS	🟩 RNCS	🟪 RNCS	RNCS	RNCS	RNCS	NCS	NCS	NCS
2011	RNCS	RNCS	RNCS	RNCS	RNCS	🟩 RNCS	🟪 RNCS	RNCS	RNCS	NCS	NCS	NCS
2012	CAPS	CAPS	CAPS	RNCS	RNCS	RNCS	🟩 RNCS	🟪 RNCS	RNCS	CAPS	NCS	NCS
2013	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	RNCS	🟩 RNCS	🟪 RNCS	CAPS	CAPS	NCS
2014	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	🟩 CAPS	🟪 CAPS	CAPS	CAPS
2015	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	🟩 CAPS	🟪 CAPS	CAPS
2016	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	🟩 CAPS	🟪 CAPS
2017	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	CAPS	🟩 CAPS

🟩 2017 cohort 🟪 2016 cohort

1.3.2 The topic of adaptation in the Curriculum and Assessment Policy Statement for the Life Sciences

The topic of **adaptation** is found in all three grades (Grade 10, 11, and 12) in the CAPS Life Sciences curriculum, as shown in Table 4. For grades 10 and 11 the word ‘adaptation’ is used in the curriculum statement to refer almost exclusively to adaptive structures, or the ‘product’ of adaptation. The document refers to the adaptive characteristics of cells, flowers, the small intestine, etc. but it does not speak of how these structures came about in the first place (see Table 4). Adaptation as a process (defined in section 1.2) is only inferred in the Grade 12 curriculum statement. In Grade 12, wording in the relatively minor reference to adaptation may infer a process and, considering that it is found in the description about natural selection, an informed educator might make the connection between the two topics. However, the link between natural selection and adaptation is not explicit in the CAPS Life Sciences curriculum.

Much of the **evolution** content in the South African CAPS Life Sciences curriculum is taught in grades 10 and 12. This is in line with the prevailing ideas of curriculum designers in the United States of America, who recommend that students study the different lines of evidence for evolution in middle school (grades 6 to 8), but not the mechanism of evolution (American Association for the Advancement of Science, 2006). The American Association for the Advancement of Science (2006) advises that the mechanisms of evolution, natural selection and adaptation, be taught between grades 9 and 12. These ideas may have had an influence on the arrangement of content in the South African curriculum.

Table 4: Adaptation-related content in the Life Sciences Curriculum and Assessment Policy Statement (Department of Basic Education, 2011b)

Grade	Topic	Content
10	Plant and animal tissues	Introduce the concept of a tissue as a group of similar cells adapted for a particular function; cell differentiation. Emphasise the relationship between their basic structure and function. (p. 26)
11	Reproduction in plants	Flowers as reproductive structures: Adaptations for pollination through (different pollinators) wind, insects and birds (South African examples only) differences and similarities. (p. 40)
	Animal nutrition	Absorption: small intestine as a region of most absorption of digested food; adaptations to increase surface area. (p. 43)
	Gaseous exchange	Human gas exchange: The structure (macro and tissue level), location, adaptations and functioning of the ventilation system (p. 46)
12	Homeostasis in humans	thermoregulation: adaptations of human skin; sweating, vasodilatation, vasoconstriction. (p. 60)
	Diversity, change and continuity.	Darwin's theory of evolution by natural selection - evolution (change) through natural selection (link to genetics): depends on variation/gene pool of inherited characteristics, and the production of more offspring than is required. Changes in the environment. Pressure leads to extinction or successful adaption. (p. 61)

1.4 PROBLEMS MOTIVATING THE STUDY

Several problems associated with students' understanding of the concept of 'adaptation' motivated this study. These problems can be divided into two broad categories. Firstly, students come to class with a range of unscientific ideas about the evolutionary topic of adaptation and, secondly, that South African students are not presented with the full and complete scientific explanation for evolutionary adaptation until Grade 12. As the sections that follow will show, these problems have a negative impact on students' understanding of the topic of adaptation, and potentially the topic of evolution as a whole.

1.4.1 Misconceptions about adaptation are frequent, and interfere with further learning

I use the word 'misconception' broadly, in this section, to mean a faulty, vague, mistaken or imperfect idea about something. I have more closely defined the term 'misconception' in Chapter 2 (section 2.2.2).

Misconceptions about adaptation and evolution are common among high school students around the world (Bishop & Anderson, 1990; Brumby, 1984; Engel Clough & Wood-Robinson, 1985a; Jungwirth, 1975; Nehm & Schonfeld, 2007). Misconceptions about structures, phenomena, and processes in the natural world are those that are at variance with scientific explanations for them (Coley & Tanner, 2015; Wandersee, Mintzes, & Novak, 1994). Misconceptions about adaptation appear in early childhood (Legare et al., 2013; Shtulman et al., 2016), are common in high school students (Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985a), occur in undergraduate tertiary-level students (Brumby, 1984), and persist into adulthood (Aron, Francek, Nelson, & Bisard, 1994; Kelemen, 1999), despite formal education (Yates and Marek, 2013; Coley & Tanner, 2015), and some even persist after intervention strategies (Jensen & Finley, 1995).

Misconceptions are problematic to science learning. Many students tend to hang on to their misconceptions and delay the acceptance of the scientific view even after instruction (Brumby, 1984; Freyberg & Osborne, 1985; Kelemen, 2011; Shtulman & Calabi, 2013). The interaction between students' experience, their innate tendency to theorise about the world around them, and the scientific content that they are taught at school, contributes to five possible outcomes for science learning, as described by Freyberg and Osborne (1985), as shown in Table 5. The goal of science education is to help students develop the "unified scientific outcome" by helping students with unscientific ideas to "restructure their ideas in useful and useable ways" (Freyberg & Osborne, 1985, p. 88). Students may not reach this intended goal if they hold on to their misconceptions. Instead students may fall into one of the four negative outcomes of science learning described by Freyberg and Osborne (1985) and summarised in Table 5.

Table 5: Five potential outcomes of science learning described by Freyberg & Osborne (1985)

Outcome	Explanation
Undisturbed children's science outcome	Students' unscientific ideas remain unchanged, even after teaching.
The two perspective outcome	Students use their unscientific ideas when out of school but learn some scientific ideas and use them to answer questions in class or in examinations or tests. Such students are able to learn scientific facts, and repeat them when needed, but do not reason scientifically.
The reinforced outcome	Ideas communicated in class by the teacher or textbook may inadvertently be misinterpreted by students as supportive of students' current unscientific ideas, which then serve to reinforce their unscientific ideas.
The confused outcome	Exposure to new information and experiences may cause students to lose confidence in their prior ideas. If new ideas are not constructed to replace them, and the sense of confidence that they provided to the student restored, the student may be left in a state of confusion and incoherence. Such a state impedes learning and reduces self-esteem.
Unified scientific outcome	Where students construct a scientific understanding of the world that they can relate to other science topics that they learn, and the world around them.

Misconceptions about evolution and adaptation are likely to be a barrier to learning in biology because, as explained by Dobzhansky (1973), understanding evolution is central to the understanding of many other biological processes and phenomena.

1.4.2 The existence of problematic alternative frameworks

The second problem motivating this study is that misconceptions are often not isolated, but consist of a number of "interlocking ideas" (McClelland, 1984, p. 1) or "sets of beliefs" (Driver, 1981, p. 94) that students have constructed about a scientific topic. The literature refers to these connected unscientific ideas as 'alternative frameworks' (Driver, 1981; Driver, Asoko, Leach, Mortimer, & Scott, 1994; McClelland, 1984; Sanders, 2014b). Alternative frameworks are 'alternative' because they do not conform to or fit in with scientific explanations of biological phenomena, and 'frameworks' because they consist of a number of connected unscientific ideas (McClelland, 1984). Whether unscientific ideas lead to alternative frameworks or alternative frameworks cause unscientific ideas is unknown.

The two alternative frameworks relevant to the topic of adaptation (discussed in greater detail in Section 2.4.2,starting on p. 33) are the 'survival of the fittest' framework and the 'evolution on demand' framework. The 'survival of the fittest' framework consists of a number of individual unscientific ideas mostly to do with the term 'fit' (see Section 2.4.2, p. 34). It suggests that the strongest or most physically fit organisms are the only ones that survive (Gregory, 2009), an idea derived from the use of the word 'fit' in common English language. The second problematic alternative framework is 'evolution on demand', discussed further in Section 2.4.2, p. 34. It is the view that organisms 'need to change in order to survive' and that individual organisms consciously initiate and control the development of the necessary adaptations. This particular alternative framework is associated with "informal, intuitive" anthropomorphic and teleological ways of thinking (Coley & Tanner, 2015, p. 210).

1.4.3 Anthropomorphic and teleological thinking may influence misconceptions

The third problem motivating this study is that 'unscientific ways of thinking' (e.g. anthropomorphism and teleology) may be the cause of unscientific ideas and alternative frameworks, both in children and adults (Gregory, 2009; Shtulman & Schulz, 2008). Two unscientific 'ways of thinking', specific to adaptation are evident in the 'evolution on demand' alternative framework: anthropomorphism and teleology (Bartov, 1981; Coley & Tanner, 2012; Kelemen, 1999; 2011). Anthropomorphism is the tendency to attribute human-like thoughts and behaviours to non-human entities, and teleology is the tendency to explain objects and events according to their function or purpose rather than their cause (Gregory, 2009; Sanders, 2014b). These 'ways of thinking' are elsewhere called 'conceptual biases' (Gregory, 2009; Kelemen et al., 2014) and are commonly used by young children trying to make sense of events in the world around them (Zohar & Ginossar, 1998). Pre-school children tend to explain the origin of objects using teleological language, and explain "events and objects" (Kelemen, et al., 2014, p. 894) as being intentionally caused, which also implies anthropomorphic thinking. These conceptual biases are problematic because they appear to limit the degree to which older students are able to comprehend evolution-related concepts (Bishop & Anderson, 1990; Kelemen, et al., 2014). Research suggests that many high school students (Settlage, 1994; Southerland, Abrams, Cummins, & Anzelmo, 2001) and university students (Kelemen & Rosset, 2009) continue to explain biological phenomena using teleological and anthropomorphic language. This may occur when younger students (under the age of 10) connect previously unrelated conceptual biases to form an integrated schema (mental framework) to explain biological events in purpose-driven and intentional ways (Kelemen, et al., 2014).

1.4.4 Adaptation, and the problem of paradoxical jargon

The language of science, especially words that are borrowed from everyday English, presents a problem to student understanding (Ashelford, 2002; Clerk & Rutherford, 2000). Common words that have been incorporated into biology are difficult to master because of their "highly specific technical meanings" (Ryan, 1985, p. 91). Words like, 'adapt', 'select' and 'fit' are common to both evolutionary biology and everyday language, but have different meanings depending on the context within which they are used (Nehm, Rector, & Ha, 2010). Students tend not to realise that some evolutionary terms have an everyday meaning that is different to the scientific meaning (van Dijk & Reydon, 2010) and tend, inappropriately, to use the everyday meaning in a scientific context (Ryan, 1985). The word 'fit', for example, in everyday English means healthy, strong, fast, or athletic, but in science it is used to refer to an organism's survival and reproductive success in its environment (van Dijk & Reydon, 2010). The same problem exists with the word 'adaptation': students tend to view adaptation as a process where individual organisms alter their characteristics through their own effort because of a certain need, an idea that is consistent with the meaning of adaptation in everyday English, as applied to humans (van Dijk & Reydon, 2010). In science, however, adaptation is defined as a characteristic of an organism that increases it's fitness, and the process by which populations of organisms increase in fitness relative to their environment (Levine & Miller, 1994) (see section 1.2). Paradoxical jargon words (like 'adapt' and 'fit') are those whose "very familiarity masks the fact that they have specialised meanings in a particular field" (Ryan, 1985, p. 91). The everyday meaning of the word 'adaptation' may cause or validate unscientific ideas and unscientific ways of thinking (teleology and anthropomorphism) about the topic of adaptation in science, which may lead to confusion and prevent meaningful learning.

1.4.5 Fragmentation problems in the Life Sciences South African Curriculum and Assessment Policy Statements

The fifth problem motivating this study is that evolution-related topics are fragmented across the grades in both the Natural Sciences (Grades 4 to 9) and Life Sciences (Grades 10 to 12) curricula in South Africa. Fragmentation is the division or separation of topics or concepts into different chapters in a textbook or different grades in a curriculum document (Tshuma & Sanders, 2015). The danger is that students may perceive fragmented information as isolated facts, and that could impede the development of accurate mental models of biological phenomena (Nehm et al., 2009; Southerland, Sinatra, & Matthews, 2001; Tshuma & Sanders, 2015). This is particularly problematic with the topic of adaptation in the South African Curriculum and Assessment Policy Statement. Students learn about adaptation in Grade 7, 8, 10, 11, and 12. This study is primarily concerned with the extent of South African students' understanding (or lack thereof) of adaptation before and after formal instruction on natural selection, in order to see if their understanding of adaptation changes after learning about natural selection. It seems unlikely that students will develop a coherent mental model (schema) of adaptation until after they are taught about natural selection in Grade 12 (unless students are exposed to the topic by some other means). Even then, the (alternative) mental frameworks of students may be so ingrained that merely teaching the mechanism of adaptation, natural selection, may not be enough to address the conceptual errors students have about the topic of adaptation.

1.4.6 Sequencing problems in the Life Sciences Curriculum and Assessment Policy Statement

Associated with the fragmentation of evolution-related content in the Curriculum and Assessment Policy Statement is a sequencing problem. Sequencing problems arise when "concepts needed to understand a new point are only dealt with later" (Tshuma & Sanders, 2015, p. 357). Natural selection is the only mechanism known to cause the development of adaptations (Futuyma, 2009). In the opinion of Sanders (2014b), if students are to fully understand the topic of adaptation, natural selection must first be explained. In the CAPS curriculum, adaptation is taught before natural selection, which is covered only in Grade 12. This may undermine the development of a coherent mental model of the concept of adaptation by students.

Two common arguments for the late inclusion of mechanistic explanations for adaptation and natural selection appear in the literature. Firstly, some contend that young students do not have the cognitive ability to understand the mechanism of adaptation and natural selection before high school (Lawson & Thompson, 1988). Settlage (1994) suggests that adaptation and natural selection are too complex for young students to understand. It is argued that students need life experience and maturity to understand such difficult concepts (Lawson & Thompson, 1988). Secondly, it is thought that students need to understand the evidence for evolution and the diversity of species on Earth in order to properly understand natural selection (The Academy of Sciences for the Developing World, 2006), and these topics are covered in Grade 10 and Grade 11 in the CAPS curriculum.

Educational researchers, however, do not all agree with these arguments. On the issue of whether or not young students are capable of understanding mechanistic explanations of evolution, some educational researchers argue that the emergence of unscientific ideas in young students ought to motivate the early inclusion of an “age appropriate […] accurate and causally comprehensive version of the theory” (Kelemen, et al., 2016, p. 894). Numerous authors (Kelemen et al., 2016; Legare et al., 2013; Shtulman et al., 2016) show that the explanations of natural selection and adaptation need not be so complex. Their studies showed that it is possible for young children to develop a causal understanding of adaptation when simpler explanations (e.g. using simple stories) are given. In fact, some educational researchers place the blame for the poor understanding of the topic of adaptation, shown in high school students, on the fact that the mechanism of adaptation is taught so late in high school (Engel Clough & Wood-Robinson, 1985a; Gregory, 2009; Settlage, 1994). Misconceptions and alternative frameworks about biological phenomena tend to appear when students are young (Legare et al., 2013; Shtulman et al., 2016) and “… if they are unchallenged from early childhood, ideas […] may become so entrenched that their habitual nature creates a significant ongoing impediment to scientific literacy” (Kelemen, 2011, p. 8). To avoid such impediments to learning, students ought to be exposed to age-appropriate explanations for adaptation and natural selection. On the issue of exposing students to evidence for evolution, it is important to realise that students don’t need to understand the history of evolution and the evidence for evolution before they learn about natural selection and the process of adaptation (as implied by American Association for the Advancement of Science, 2006; Johnson et al., 2015). Research (Kelemen, 2011; Kelemen et al., 2014; Shtulman et al., 2016) shows that young students can understand the mechanism of adaptation before they learn about evidence for evolution, so the topics of adaptation and natural selection should not be avoided or delayed for this reason.

1.5 AIMS OF THE STUDY

This study had four broad aims. Firstly, in light of the fact that, by the start of the study, the sample group had been exposed to the topic of adaptation several times in their schooling (Grades 7, 8, 10, and 11), I wanted to find out if students understand adaptation to be more than a product, but a process also. Then, after they were taught natural selection, does their understanding of adaptation become more scientific? I therefore wanted to determine the nature of Grade 12 students’ understanding of adaptation before they were taught about natural selection in Grade 12, and then again, after they were taught about natural selection. Secondly, I wanted to find out which concepts were missing from their explanations of adaptation. This information could be used to inform the planning of lessons on adaptation. Thirdly, I wanted to identify the common misconceptions Grade 12 students have about the concept of adaptation (again before and after learning about natural selection) and establish how many of these misconceptions belong to the various alternative frameworks typically associated with adaptation. Finally, I wanted to find out what sort of language (anthropomorphic, teleological) students used to communicate their ideas about adaptation.

1.6 RESEARCH QUESTIONS

Research aims are generally broad and non-specific. I therefore used research questions to narrow down what it was I specifically wanted to investigate. Research questions should be specific, precise, and lay out the testable objectives of the study in greater detail, in order to direct research (Fraenkel, Wallen, & Hyun, 2012).

One main research question, with several sub-questions, guided this study:

What is the nature and extent of Grade 12 Life Sciences students' understanding of biological adaptation, before and after learning about natural selection?

a. What is the nature and extent of the scientific concepts about biological *adaptation* held by the students, before and after learning about *natural selection*?
b. What essential concepts are missing from students' explanations of biological *adaptation*, before and after learning about *natural selection*?
c. What is the nature and extent of the students' unscientific ideas about biological *adaptation*, before and after learning about *natural selection*?
d. To what extent do students exhibit alternative frameworks when explaining *adaptation*?
e. To what extent do the students use anthropomorphic and teleological language in their explanations of *adaptation*?

1.7 THE STRUCTURE OF THE DISSERTATION

A number of problems about the topic of adaptation motivated this study. These problems are outlined in Chapter One. Chapter Two provides the literature-based conceptual framework for the study. It discusses important terminology, elaborates on concepts important to the study, provides evidence to show that adaptation is a difficult topic for students around the world to understand, and establishes the link between adaptation and evolution. Chapter Three then lays out the research design and methods, including aspects of validity and reliability and how these concepts were applied to the data-gathering and data-analysis procedures. Chapter Four presents the results of the data analysis in terms of the aims and research questions. Chapter Five then discusses the implications of the conclusions and their relevance to evolution education. It points out the strengths and weaknesses of the study, and further research possibilities that arise from this project.

Chapter 2

Conceptual framework for the study

Having already outlined the context and the problems that motivated this study in the previous chapter, this chapter moves on to show the development and structure of the conceptual framework.

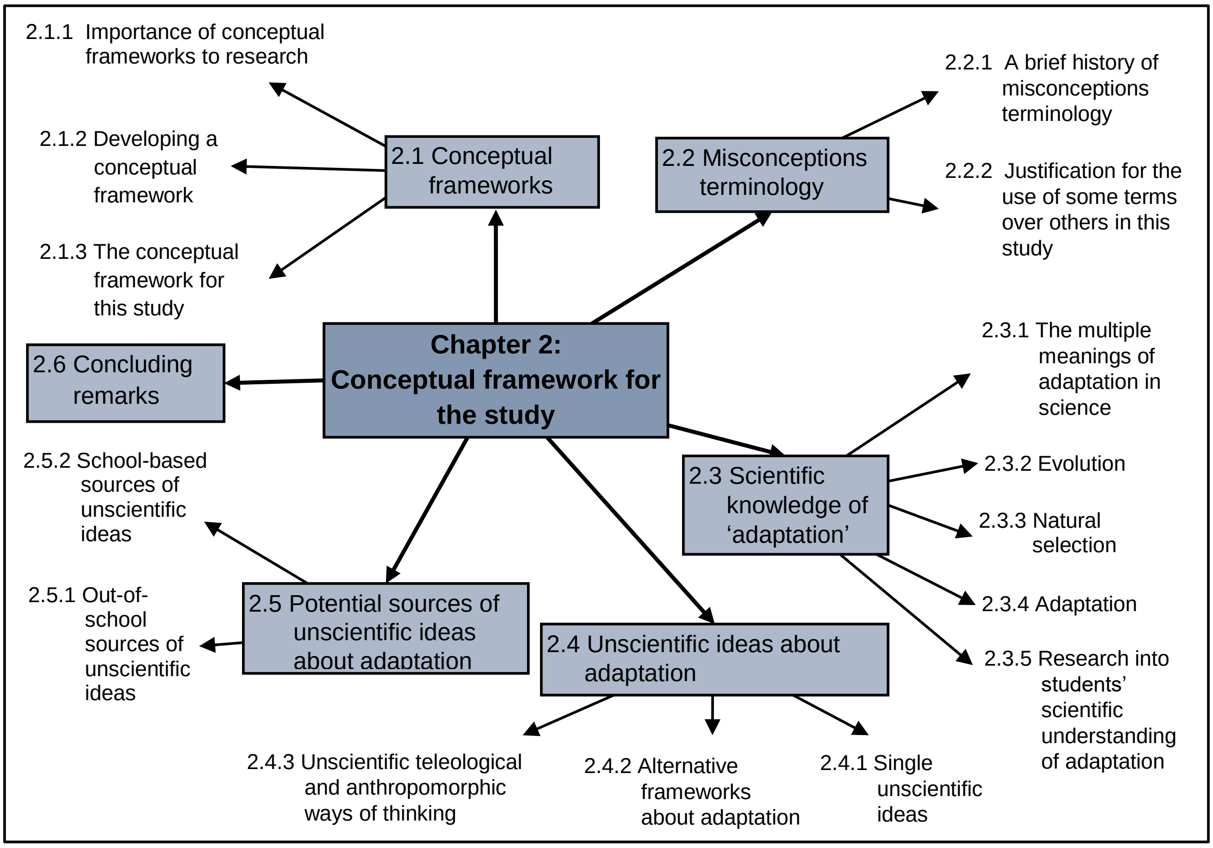

Figure 2: Structure of Chapter 2

2.1 CONCEPTUAL FRAMEWORKS

Conceptual frameworks are an important and necessary component of any research endeavour (Maxwell, 2005; Miles & Huberman, 1994a; Tamene, 2016). In their most basic form, conceptual frameworks operate as a "map of theories and issues" (Leshem & Trafford, 2007, p. 99) that work to both orientate the researcher and to plot the way to the final objective. More specifically, a conceptual framework explains "either graphically or in narrative form, the main things to be studied – the key factors, constructs or variables – and the presumed relationship among them" (Miles & Huberman, 1994a, p. 18). However, the conceptual framework is not limited to these key factors, but may also reveal the "assumptions, expectations and beliefs" of the researcher (Maxwell, 2005, p. 33). The ideas and beliefs of researchers are influenced and informed by the literature, which is a key role player in the development of conceptual frameworks (Antonenko, 2014; Maxwell, 2005; Miles & Huberman, 1994a)

However, conceptual frameworks provide more than just a literature review. Literature reviews are often descriptive, merely providing a synthesis of important elements in the literature that relate to a particular study. Literature reviews can be problematic because, as Maxwell (2005, p. 35) notes, the literature can be “partial, misleading or simply wrong”. It is therefore important that researchers approach the literature with a willingness to critically evaluate the findings, which informs both the theory and validity of a study (Maxwell, 2005). A conceptual framework is distinct from a literature review in that it links relevant concepts from the literature and demonstrates how empirical evidence, theories, and concepts inform the formulation of the research design (Antonenko, 2014).

2.1.1 Importance of conceptual frameworks to research

Conceptual frameworks are pivotal to a research study for a number of reasons. Firstly, a conceptual framework highlights the problem motivating the research, something that is going on in the world that has negative consequences, and about which the researcher would like to understand more (Maxwell, 2005; Tamene, 2016). To find out more the researcher must look to the existing body of knowledge on the topic, the literature (Antonenko, 2014; Leshem & Trafford, 2007). Building a conceptual framework out of the literature, “facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed” (Webster & Watson, 2002, p. xiii) which, in turn, advances knowledge. Secondly, conceptual frameworks help researchers develop, assess and refine their goals (Maxwell, 2013). Research goals explain why the research is worth doing in light of the problem the researcher has identified. The researcher’s goals are informed by the relevant current theory and knowledge that makes up the conceptual framework. Thirdly, conceptual frameworks provide the basis for developing and refining the research questions. The research questions relate to the specific variables of the research problem that researchers want to investigate (McMillan & Schumacher, 2010), and spell out what answers they seek. Other ideas and examples from previous studies give the researcher insight into how best to narrow down the research questions from the general goal of the research (McMillan & Schumacher, 2010). Fourthly, conceptual frameworks inform the selection of research methods (Maxwell, 2013; Miles & Huberman, 1994a). As a conceptual framework is built up and takes shape, the researcher seeks the best research methods to answer the research questions. While some may select methods in line with their ontological leanings and preferences, others will select methods based on knowledge gaps identified in the literature (Leshem & Trafford, 2007; Maxwell, 2005). Fifthly, conceptual frameworks help the researcher identify potential threats to the validity of the conclusions as comparisons are drawn with those of other studies (Miles & Huberman, 1994a), and, finally, conceptual frameworks are indispensable during the interpretation of the results.

2.1.2 Developing a conceptual framework

A conceptual framework is **developed** or **constructed** for a specific research project by a researcher or group of researchers. It is not something that one passively stumbles upon, or finds in its entirety in other research projects, journal articles or books (Maxwell, 2005). Conceptual frameworks are as unique as the researchers who develop them and are the outcome of their interaction with the literature and other researchers in the field (Maxwell, 2005).

There are two important steps in the development of a conceptual framework. The first is identifying the major constructs of the study, something Miles and Huberman (1994a) refer to when they suggest that “theory building relies on a few general constructs that subsume a mountain of particulars”. Miles and

Huberman (1994a, p. 18) call these general constructs “intellectual bins” which act as containers into which other more specific sub-constructs can be placed. Another way of conceptualising this is to view each construct as a “module” (Becker, 2007), an idea that is a significant part of the overall argument and, while self-contained, is linked to the other modules in the study. Establishing the links between these modules or constructs is the important second step in the construction of a conceptual framework (Miles & Huberman, 1994a).

The constructs of a conceptual framework and the links between them are derived from four sources. Conceptual frameworks, firstly, emerge from researchers’ personal experience (Leshem & Trafford, 2007). Experiential knowledge is the personal experience and expertise that a researcher brings to the project that can be a “source of insight, hypotheses and validity checks” (Maxwell, 2005, p. 45). The use of experiential knowledge in research is contentious to some (see Maxwell, 2005) as it opens the door for subjectivity and bias. However, not to use background knowledge or prior experience is, in the words of Miles and Huberman (1994a, p. 17), “self-defeating”. Prior experience helps a researcher to “decipher details, complexities, and subtleties that would elude a less knowledgeable observer” (Miles & Huberman, 1994a, p. 17). Without the unique perspectives and ideas of individual researchers there would be little originality in research as there would be nothing new because what is being said is a repeat of what has already been stated (Becker, 2007). The second important source of constructs is “prior theory” (Maxwell, 2005, p. 49). The word ‘theory’ refers to two or more concepts linked by a relationship (Miles & Huberman, 1994a). Theories are important to all aspects of life (including research projects) because theories attempt to explain why something in the world is the way it is, and have value in making predictions. Previous theories help researchers understand what is going on with the major concepts in their study, help the researcher interpret the data, and act as a stepping stone to new theory development (Maxwell, 2005). Becker explains that new theory development need not be totally original, but can be a matter of linking concepts from previous theories in new ways and filling in any gaps. He explains:

> “… you needn’t invent the whole thing. Other people have worked on your problem or problems related to it and have some of the pieces you need. You just have to fit them in where they belong” (Becker, 2007, p. 143).

The third source of constructs for a conceptual framework is a pilot or exploratory study. Piloting an instrument can be used as much to test theories and hypotheses as to assess the validity (discussed in Chapter 3) of the instrument (Maxwell, 2005). Maxwell (2005) points out that pilot instruments ought to be used as much to establish relationships between concepts in one’s conceptual framework as to clarify possible problems with the instrument itself. The fourth source of constructs in a conceptual framework is the use of ‘thought experiments’. ‘Thought experiments’ use experiential knowledge and prior theory to develop plausible explanations for phenomena without physically conducting any research (Maxwell, 2005). The idea is to use what is known about a phenomenon to explain what is unknown. The deliberate and intentional application of thought experiments “encourage creativity and a sense of discovery, and can make explicit the experiential knowledge that you possess” (Maxwell, 2005, p. 69). Pilot studies and thought experiments did not apply in my case, and are not discussed further.

2.1.3 The conceptual framework for this study

The conceptual framework for this study is represented visually in Figure 3, in addition to the alternate narrative form (discussed by Miles & Huberman, 1994a), in the rest of the chapter. The major constructs for this study are presented in the dark blue boxes in the figure, and are "misconceptions terminology"; "unscientific ideas about adaptation"; "scientific explanations", and "possible causes of the problem". The colour distinction between the boxes represents the hierarchical order, with the dark blue boxes representing the major constructs, followed by boxes with solid lines and 'no fill' representing sub-topics, followed by boxes with dashed borders and no fill. Directional arrows illustrate the relationships between the constructs, with the direction of the arrows indicating the perceived direction of influence. The major constructs are joined to the sub-topics by solid lines, indicating that the sub-topics are a part of that major construct. Dashed lines join sub-topics with other important ideas. The boxes with the pink and blue fill around the 'unscientific ideas' (and related sub-topics) and 'scientific explanations' (and related sub-topics) respectively, highlight the important conceptual distinction between, and separation of, scientific and unscientific ideas about adaptation.

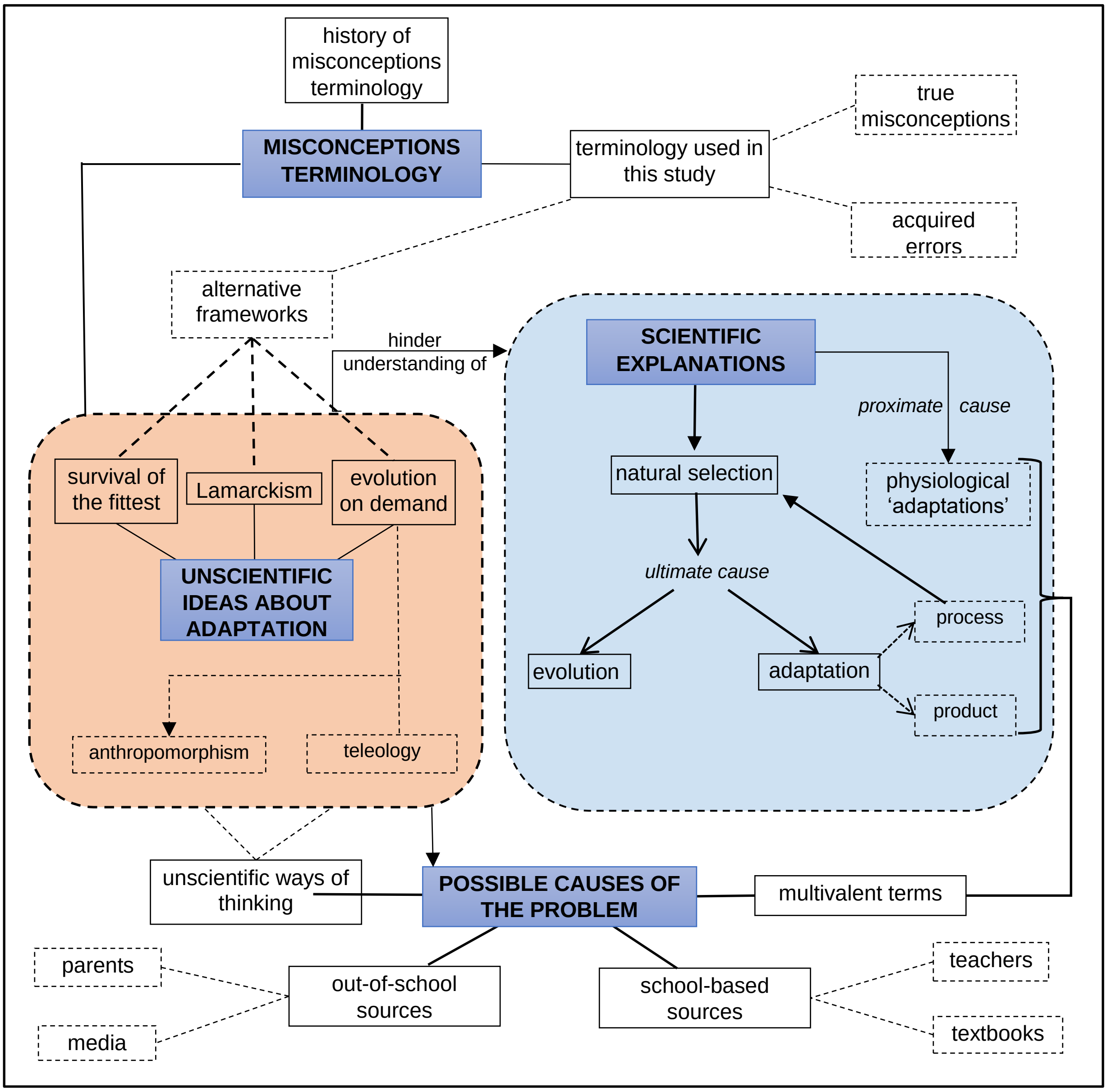

Figure 3: Conceptual framework for the study

2.2 MISCONCEPTIONS TERMINOLOGY

Many terms and phrases are used in the literature to describe students' erroneous ideas about science. This is a problem for 'novice' researchers because it "offers more confusion than clarification" (Modell, Michael, & Wenderoth, 2005, p. 21) and it "may block the […] path to understanding the alternative conceptions literature" (Wandersee, Mintzes, & Novak, 1994, p. 178). Some creative metaphors such as "thicket of terminology" and "mired in a morass of terms" have also been used to describe this problem of terminology (Wandersee et al., 1994, p. 178). The many terms in the literature stem from the different worldviews of researchers (discussed in the next section) and their understanding of student difficulties (Abimbola, 1988). Researchers have felt that one term, such as 'misconception', is too generic and does not effectively "emphasize specific characteristics of the conceptual difficulty" (Modell et al., 2005, p. 20).

2.2.1 A brief history of misconceptions terminology

Misconceptions terminology has evolved out of two broad philosophical schools of thought in education, empiricism and the 'new' philosophy of science (Abimbola, 1988). He claims[1] that empiricists tend to view students as empty vessels that need to filled with correct science knowledge, supposing that students are passive recipients of knowledge rather than actively involved in its construction, and claims that empiricists tend to view students' conceptions negatively. The terms empiricists use to describe unscientific ideas tend to imply that students' incorrect ideas, relative to an expert's knowledge, are valueless. Words like 'erroneous conceptions', 'misconceptions', 'misunderstandings', 'erroneous idea' etc. are commonly used by empiricists in reference to student conceptions of science phenomena (Abimbola, 1988). 'New' philosophy of science researchers argue that students are not empty vessels to be filled with knowledge, but are active participants in the construction of knowledge (Driver et al., 1994). Abimbola (1988) distinguishes between two sub-groups of researchers within the new philosophy of science, revolutionary and evolutionary. He explains that revolutionary researchers tend to view students' unscientific ideas negatively and as being a potential barrier to new learning, very similar in many respects to the views Abimbola claims are held by empiricists. He suggests that these views may be remnants of the empirical view in some researchers. The awareness-disequilibrium-reformation approach to conceptual change distinguishes revolutionist researchers from empiricists (Abimbola, 1988). Revolutionists share some common terms with empiricists when referring to students' scientifically incorrect ideas, such as 'misconceptions', 'erroneous ideas' and 'misunderstandings' (Abimbola, 1988). Researchers with an evolutionary perspective, on the other hand, argue that students' unscientific ideas about the natural world have value in other (non-scientific) contexts (Abimbola, 1988; Coley & Tanner, 2012; Driver et al., 1994). Such researchers believe that even ideas that scientists would consider to be incorrect have value to help students reconcile unscientific ideas with new scientific ideas taught in class. These researchers tend to use more neutral words like 'existing conceptions', 'prior conceptions', 'alternative conceptions', and 'alternative frameworks' to describe unscientific ideas developed prior to learning.

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[1] Abimbola's claims about empiricists are generalisations that do not hold true for all empiricists, and should be treated with caution.

2.2.2 Justification for the use of some terms over others in this study

A number of authors have suggested that the term 'alternative conceptions' be used to refer to ideas that students have constructed from their experience of the world around them but that do not conform to science (Abimbola, 1988; Modell et al., 2005; Wandersee et al., 1994). The problem with this phrase is two-fold. Firstly, it ascribes "intellectual respect on the learner who holds those ideas" (Wandersee et al., 1994, p. 178). Such affirmation is counter-productive to education and conceptual change because it sends mixed messages to the student by affirming the students' erroneous ideas as being of equal value to that of science knowledge. Secondly, it is sometimes confused with the similar sounding, but distinctly different phrase 'alternative framework' (Wandersee et al., 1994). The phrase 'alternative conceptions' is not used in this study. The terms that are, are discussed further in the following sections.

Unscientific ideas

Unscientific ideas can be divided into two general categories based on their origin; those that have been internally constructed by students and those that are acquired, or rote-learned, from an outside source (Brumby, 1984; Tshuma & Sanders, 2015; Wandersee et al., 1994). In this study, the former are called 'misconceptions'. The term 'misconception' is preferred to other phrases like 'alternative conception' because it already has meaning to the layperson and "readily conveys the concept of an idea at variance with current scientific thought" (Wandersee et al., 1994). Misconceptions are "scientifically incorrect ideas which individuals have constructed as they attempt to meaningfully incorporate ideas into their cognitive structure to form mental models [frameworks] or schema that represent their understanding" (Tshuma & Sanders, 2015, p. 355). Misconceptions may inform, or be informed by, alternative frameworks, and are problematic because they tend to be resistant to change and are likely to interfere with new learning (Kelemen et al., 2014; Rollnick, 2000). Acquired errors are ideas that students have "rote-learned, or memorised" (Brumby, 1984) from an outside source (e.g. a textbook, parent, teacher, television) and that have not been internally constructed by the student (Tshuma & Sanders, 2015). Acquired errors are distinct from misconceptions because they have not been constructed by the user and it is thus likely that they will not be as resistant to change as true misconceptions.

The term 'misconception', in the everyday sense of the word (Wandersee at al., 1994) has been used frequently in Chapter 1 and in Chapter 4 to describe unscientific ideas. I have not used the word 'misconception' to refer to internally constructed unscientific ideas specifically, but to scientifically incorrect ideas generally, which includes students' acquired errors. The reason is that distinguishing between misconceptions and acquired errors is generally difficult. As Fisher and Lipson (1986, p. 787) note, "… it is somewhat difficult to establish that a particular misconception exists (i.e., multiple lines of evidence are usually required)". Therefore, I have used the terms 'unscientific ideas' and misconception interchangeably in this study.

Alternative frameworks

A cognitive framework is a lattice of interconnected ideas that people use to interpret the world around them. A person's framework is regarded as being 'alternative' when either their ideas, or the connections between their ideas, do not comply with scientific explanations of natural phenomena. Alternative frameworks integrate and connect a number of misconceptions and acquired errors, though it is unknown whether alternative frameworks cause misconceptions or whether misconceptions lead to alternative frameworks (see Section 2.4.2, page 33).

It is important not to confuse the term ‘alternative conception’, used by some authors when referring to misconceptions, with that of ‘alternative framework’. The term ‘alternative framework’ refers to the organisation of, and connection between, ideas, and not to the individual ideas themselves (Abimbola, 1988). The existence of such frameworks is inferred by researchers from what students discuss during interviews or diagnostic activities (Abimbola, 1988; Wandersee et al., 1994). When a number of unscientific ideas connect in a student’s thinking they make up an alternative framework. Two particular alternative frameworks of interest to this study on student understanding of adaptation are the ‘evolution on demand’ alternative framework and the ‘survival of the fittest’ alternative framework, discussed further on page 34.

2.3 SCIENTIFIC KNOWLEDGE OF ‘ADAPTATION’

The scientific knowledge of natural selection, adaptation and evolution are an important part of the conceptual framework for this study because students’ responses to the questions on the instrument had to be evaluated for their scientific merit.

2.3.1 The multiple meanings of ‘adaptation’ in science

As explained briefly in section 1.2 (starting on p. 3), the word ‘adaptation’ has meaning in both scientific and everyday language contexts. This is largely because the word ‘adaptation’ has been “co-opted” (Nehm, Rector, & Ha, 2010, p. 606) from everyday language for use in science. In everyday language adaptation has to do with change: to adapt something is to change it for a particular purpose (Ashelford, 2002). In everyday English, this general meaning is used to speak of minor or subtle changes made to something, like a tool or a movie, so that it suits another application (Ghiselin, 1966). The meaning of adaptation in science, however, is distinct from the everyday meaning of the word. This presents conceptual difficulties for students in science when trying to understand the concept of adaptation (Ashelford, 2002; Lucas, 1971; Williams, 1966). The labels ‘lexical ambiguity’, defined as “…multiple meanings for identical words” (Rector, Nehm, & Pearl, 2013, p. 1108), and, ‘paradoxical jargon’, defined as familiar words with specialised meanings in science (Ryan, 1985, p. 91), are used to describe the problematic nature of ‘adaptation’ in science.

The different meanings of adaptation in everyday language and science is not the only likely cause of conceptual difficulties for students, because even within science there are several meanings for ‘adaptation’ (Ashelford, 2002; Lucas, 1971; Rector et al., 2013). Adaptation is, therefore, a “multivalent” word (Nehm et al., 2010, p. 605) that is “susceptible of (sic) many applications, interpretations, meanings, or values” (Oxford University Press, 2017). A number of authors point out that in science adaptation has two elements, namely the **product** (National Academy of the Sciences working group on teaching evolution, 1998; van Dijk & Reydon, 2010) and the **process** (Ashelford, 2002; Futuyma, 2009; Lucas, 1971) of adaptation, as illustrated in Figure 4.

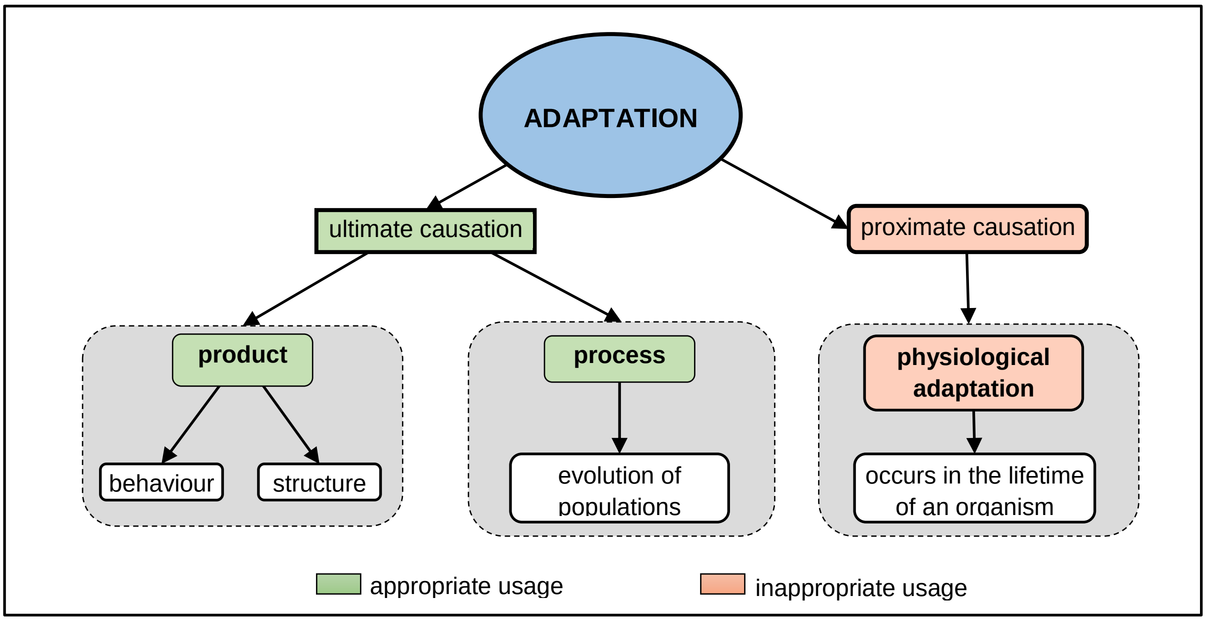


Figure 4: Meanings of adaptation in science

The 'product' and 'process' of adaptation are both a significant part of the definition of adaptation for this study (see section 1.2 of Chapter 1). The products of adaptation are those characteristics, structural adaptations (Ashelford, 2002; Bock, 1980; Futuyma, 2009; Ridley, 2004; West, 2006; Department of Basic Education, 2011a, 2011b; Freeman & Herron, 2007; Futuyma, 2009) or behavioural adaptations (Ashelford, 2002; Department of Basic Education, 2011a; Lucas, 1971; National Academy of the Sciences working group on teaching evolution, 1998), that are the result of natural selection. Adaptations give a survival and reproductive advantage to the organisms that bear them. The word 'adaptation' is also used to refer to a process of change that is NOT evolutionary adaptation. It is often ambiguously used to refer to changes that occur in an organism's lifetime, like physiological changes such as an increase in red blood cells during acclimatisation to high altitude (Ashelford, 2002; Bock, 1980; Futuyma, 2009; West, 2006). While the historical origin of physiological changes in living organisms may be natural selection occurring in populations in the distant past, the occurrence of such changes in the lifetime of individual organisms is explained by physiological processes and not by natural selection. Therefore, physiological changes that occur in the lifetime of an individual organism are not the result of adaptive mechanisms but rather the result of the organism's physiology. Because this distinction is important, and leads to a recommendation that physiological changes should not be referred to as 'adaptations', it is discussed in more detail below.

In his now well-known paper, *Cause and Effect in Biology*, Mayr (1961) noted that for any effect in biology there may be numerous causes and that these causes can be broadly divided into two categories, 'proximate' and 'ultimate' causes (see Figure 4). Proximate causes control the immediate physiological response of individual organisms to their environment. Ultimate causes explain the evolutionary history of natural phenomena (e.g. natural selection). Consider the following example (taken from Lucas, 1971). Striking similarities in structure and function exist between the thickened skin on the bottom of human feet and calluses that develop on the hands (e.g. of a gardener). While both the thickened skin under human feet and the calluses on gardeners' hands are products of a process, the cause of these processes is significantly different and easily confused. Calluses on the hands come and go through the use or disuse of the hands in some mechanical way and, therefore, have a physiological explanation. At no point is the genetic information altered or carried through to the next generation. The thickened skin under the human foot is the result of natural selection over generations and is heritable. While the result of the two process is similar (calluses, thickened skin) the causative mechanism is different. Mayr (1961) describes these two sets of causes as follows:

> "…proximate causes govern the responses of the individual (and his organs) to immediate factors of the environment while ultimate causes are responsible for the evolution of the particular DNA code of information with which every individual of every species is endowed" Mayr (1961, p. 1503).

Thus, the thickened skin under human feet has an ultimate cause (evolution), having developed as a result of "…many thousands of years of natural selection" (Mayr, 1961, p. 1503) while the calluses on the hands are an immediate response to the environment and, therefore, have a proximate cause.

The human tendency to explain proximate and ultimate causes teleologically, in light of a pre-determined end or purpose, such as survival is inappropriate and misleading when used to explain the causes of natural phenomena (see Section 2.4.3, p. 36). However, there are some seemingly goal-directed processes and activities in the natural world that deal with proximate causations. These are called teleonomic processes. Teleonomic processes are those processes or behaviours that owe their apparent goal-directedness "to the operation of a program (sic) […] that culminates in a pre-determined end-point or goal" (Mayr, 1992, p. 127 & 128). The programme that governs teleonomic processes involves an organism's genetic material and it exists long before the initiation of the apparently 'goal-directed' process (Mayr, 1992; Sanders, 2014b). Teleonomic processes in the natural world are seen in the migratory, reproductive, and courtship behaviour of organisms, which end at a specific location (migration) or with a sexual act (reproductive behaviours).

Mayr's distinction between proximate and ultimate causes in biology is not without its critics. A number of authors argue that proximate causes are intertwined with ultimate causes so that it is impossible to distinguish one from the other in terms of their effect on evolutionary change in populations of organisms (Haig, 2013; Laland, Sterelny, Odling-Smee, Hoppitt, & Uller, 2011). For example, while Laland et al. (2011) agree that the female peahen's preference for certain peacock tails co-evolved with the evolution of peacock tails in the peacock population, they argue that the preference of the female peahen was originally proximate. The Laland et al. (2011) argument that distinguishing between ultimate and proximate causation is not always definable, has merit. They don't accuse Mayr (1961) of error, they simply note that the proximate/ ultimate distinction is more complex than Mayr's paper suggests. Haig (2013) is more dismissive of the proximate/ ultimate distinction than Laland et al. (2011). Haig (2013) accuses Mayr (1961) of having the ulterior motive of promoting evolutionary biology over functional biology, and for creating a false dichotomy between functional and evolutionary biology. Haig (2013) takes aim at Mayr's philosophy, rather than his biological argument and, in my opinion, does exactly what he accuses Mayr (1961) of doing – promoting the interests of one form of biological study (functional) over another (evolutionary).

In order to overcome the conceptual difficulties associated with the multiple meanings of 'adaptation' in science, Ashelford (2002) argues that a clear distinction must be made between the different explanations of adaptation:

> "teaching the different meanings of adaptation under one banner can lead to conceptual difficulties in our teaching, especially if we fail to distinguish adaptation as a long-term change in a population of organisms from a physiological, behavioural or developmental response that occurs within a single lifetime" (Ashelford, 2002, p. 98).

Ashelford suggests that teachers call non-evolutionary adaptations “physiological processes" instead. In my opinion, the term “physiological processes” is too broad and can be applied to any system in the body, not just those responding to environmental stimuli. West (2006) provides a helpful solution to the problem. West (2006, p. 26) uses the word ‘physiological response’, as opposed to ‘physiological adaptation’, and uses ‘evolutionary adaptation’ to refer specifically to long-term evolutionary change. I contend that it is inappropriate to use the word ‘adaptation’ to refer to short term physiological changes, which should instead be referred to as ‘physiological responses’. The term ‘adaptation’ should be reserved for use in the context of evolution only.

2.3.2 Evolution

The word ‘evolution’ is used in a variety of contexts (language, technology, the economy, culture etc.) to mean ‘change over time’ (van Dijk & Reydon, 2010). Biological evolution, however, specifically refers to a “change in trait distributions of populations” (Freeman & Herron, 2007, p. 90) or to a “change in the properties of groups of organisms over the course of generations” (Futuyma, 2014, p. 3). For these ‘changes’ to be considered evolutionary they must be passed down through the genetic material of many generations of organisms, accumulating until the population evolves (Futuyma, 2009).

As pointed out in Chapter 1, the theory of evolution is built on two main ideas, and the concept of adaptation is important to both. The first is ‘descent by modification’, the idea that all organisms have descended from one or a few ancestral organisms (Campbell et al., 2015). Descent by modification helps to explain three facts about all living things, 1) that organisms are suited to their environments, 2) that there is great diversity of life on the Earth and, 3) unity exists between living organisms on Earth (e.g. presence of homologies) (Campbell et al., 2015; Dobzhansky, 1973). Darwin argued, and science has since shown, that organisms have evolved through the incremental accumulation of adaptations in populations over many generations (Campbell et al., 2015). The second idea, also known as the most significant idea in the history of human thought (Futuyma, 2009), is natural selection.

2.3.3 Natural selection

While the idea of evolution had been around for a while before Charles Darwin, he was the first (though credit must go to Alfred Wallace as well) to provide a credible scientific explanation for the cause of evolution, natural selection (Campbell et al., 2015; Futuyma, 2009). Natural selection is a process that involves changes in the frequency and distribution of traits in populations (Freeman & Herron, 2007). Kelemen et al. (2014, p. 893) note that “[a]daptation by natural selection is a core mechanism of evolution”. While three other “forces of evolution” exist (Ridley, 2004, p. 394) – genetic drift, mutation, and gene flow – they tend to be spontaneous and haphazard. Natural selection is the only known mechanism that causes sustained, systematic and directional changes within populations over generations (Futuyma, 2009).

Natural selection is a ‘mindless’ process that operates on individual organisms but causes the adaptation of entire populations. Natural selection occurs in all populations and operates on phenotypic variation through differential reproduction and heredity (Campbell et al., 2015; Futuyma, 2009; Ridley, 2004). Populations of organisms display trait variations in size, colour, pattern arrangement, etc. which can be very slight (e.g. pattern arrangement) or more marked (e.g. colour differences). Such variations lead to differences in survival and reproductive success among individuals in the population, where each organism must cope with the demands that the environment places on it. Organisms with advantageous variations are likely to be more ‘successful’ and survive to reproduce more offspring than other organisms in the population. Such organisms will pass their advantageous characteristics on to more individuals in the next generation, than organisms without the favourable variation, that are likely to be less ‘successful’, surviving for a shorter period and thus producing fewer offspring. Such organisms will pass their genetic information on to fewer organisms in the next generation. The term ‘Darwinian fitness’ is used to describe those organisms in a population that are able to produce more, viable offspring than other organisms in the population (Campbell et al., 2015; Futuyma, 2009). Over many generations, the variable survival and reproduction rate of some organisms over others will lead to more individuals in the population possessing the advantageous traits, making the population better suited to the environment (adaptation). Natural selection thus operates on phenotypic variations in populations, improving the reproductive success of some organisms and diminishing the reproductive success of others (Futuyma, 2009; Gregory, 2009; van Dijk & Reydon, 2010).

Natural selection operates on the inherent variation that exists in every population. New variations are frequently introduced into populations in one of two ways. The first is by the mixing up of existing genetic material, which occurs during the formation of gametes (genetic recombination by crossing over during prophase I of meiosis; the random movement of chromatids to different poles during anaphase I of meiosis; and the random assortment of chromosomes when gametes are formed). This leads to new combinations of alleles in an individual organism’s gametes, giving rise to new genotypes (Freeman & Herron, 2007; Gregory, 2009b). This process is aided by random fertilisation of the gametes (Campbell et al., 2015). The second mechanism for introducing variation between individuals in a population is that completely new variations are caused when mutations occur during the transcription of DNA, if certain bases are deleted, duplicated, inverted or translocated (Campbell et al., 2015). Mutations can generate new alleles for natural selection to operate on (Freeman & Herron, 2007). Mutations occur randomly and without purpose to the individual or the environment and have three possible outcomes; they can be negative, neutral or beneficial to an individual organism (Gregory, 2009; van Dijk & Reydon, 2010). While many mutations are neutral and of no value to the process of natural selection, most have a negative effect on the survival and reproduction of an organism and are unlikely to be inherited by future generations because those with the trait tend to die before passing it on (Futuyma, 2009). A small number of mutations may be beneficial, contributing to the survival, and to more offspring being produced (Gregory, 2009). Over many generations, the proportion of individuals with the beneficial trait will increase in the population, and those without the trait will decrease in number in the population (natural selection), leading to the populations increased fitness in its niche environment, by adaptation. It is important to emphasise, though, that because mutation and recombination occur during pre-natal development, it affects the phenotypes of postpartum organisms. In other words, individual organisms do not change. Instead, the frequency of certain traits in the population changes over a number of generations by being passed to some of the offspring (Gregory, 2009).

Genetic inheritance is essential for the process of adaptation. Darwin was aware of this, even though he had no concept of genetics. Darwin (cited by Gregory, 2009, p. 159) said, “Any variation which is not inherited is unimportant for us”. The introduction of new alleles into a population through mutation would have no evolutionary effect if genetic inheritance did not take place (Futuyma, 2009; Gregory, 2009). Populations only adapt if the traits of the previous generation are heritable. Freeman and Herron (2007, p.90) note, “only when the survivors of selection pass their successful phenotypes to their offspring, via genotypes that help determine the phenotypes, does natural selection cause populations to change from one generation to the next”. Thus, inheritance is an important aspect in the adaptation of populations.

2.3.4 Adaptation

Adaptation and natural selection are intricately and inextricably linked (Bock, 1980). Natural selection leads to adaptation (Gregory, 2009), as “natural selection is the only known mechanism to cause the evolution of adaptations” (Futuyma, 2009, p. 279). Without natural selection, there would be no adaptation. A population becomes better suited to the environment that it lives in over many generations through the process of adaptation (Gregory, 2009; van Dijk & Reydon, 2010). While natural selection has to do with the reproductive capacity and survival of individual organisms, adaptation is specific to population level changes (Futuyma, 2009; van Dijk & Reydon, 2010). Adaptation is an ongoing and ever changing phenomenon directed by natural selection.

As mentioned earlier, the ‘process’ and the ‘product’ of adaptation (Levine & Miller, 1994) have evolved by natural selection (Gould & Vrba, 1982). This means that characteristics that have arisen through genetic drift, gene flow, or those co-opted for another purpose (exaptations - e.g. bird feathers were initially for insulation, co-opted for use in flight) are not adaptations (Gould & Vrba, 1982). While it is easier to explain adaptation by referring to some traits as ‘advantageous’ and others as ‘having no advantage’, the reality is that populations are made up of organisms with a variety of traits and, therefore, varying degrees of fitness (Van As, du Preez, Brown, & Smit, 2012; van Dijk & Reydon, 2010). Thus the degree to which an organism is ‘fit’ or ‘less fit’ for its niche is relative to the traits of other organisms in the population, and to the environment (van Dijk & Reydon, 2010). Thus, a population does not consist of a group of individuals with a high degree of fitness and another with a low degree of fitness, but of individuals with varying degrees of fitness and, therefore, varying degrees of reproductive success. This is important when the population is exposed to new environmental pressures. If the environment changes, individuals that were ‘more fit’ may become ‘ less fit’ and individuals that were ‘less fit’ may become ‘more fit’. Gregory (2009, p. 159) states, “traits that have now become fit may have been present long before the current environment arose, without having conferred any advantage under previous conditions”.

2.3.5 Research into students’ scientific understanding of adaptation

When reviewing the literature it became clear that, for a number of reasons, it would be difficult to establish generalisable claims about students’ scientific understanding of the topic of evolutionary adaptation. Firstly, only half of the more than twenty papers reviewed on students’ understanding of adaptation gave usable frequencies of students’ understanding of the relevant concepts. Of these, six studies gave useable frequencies on student understanding of natural selection as an important aspect of adaptation (see row 1 of Table 6) and only four studies gave frequencies of students’ understanding of other concepts more directly relevant to adaptation (see Table 6). A further study, Jensen and Finley (1996), provided research pertaining to adaptation, but their interest was in assessing the overall **change** in the frequency of adaptation-related concepts of individual students and did not provide frequencies of understanding of adaptation-related topics for the sample. Furthermore, the focus of their study was more to do with assessing the merits of different forms of instruction on the sample’s understanding of adaptation topics than on assessing students' scientific ideas, so their paper was omitted from this review. Secondly, it was difficult to establish a general idea of student understanding of adaptation because, while a number of authors point out that the topic of biological adaptation is difficult for students to understand (e.g. Engel Clough & Wood-Robinson, 1985a; Gregory, 2009; Kelemen et al., 2014; Lucas, 1971; Shtulman, Neal, & Lindquist, 2016; van Dijk & Reydon, 2010), few provide evidence to support this assertion. Thirdly, many of the papers reviewed student understanding of **natural selection**, which may seem less relevant to a study on the topic of adaptation. However, because the topics of adaptation and natural selection deal with many of the same important concepts (e.g. variation in the population as a requirement for the process, and the requirement that advantageous traits be heritable), frequencies of concepts about natural selection that are applicable to adaptation have also been reported in Table 6. The fourth reason that it was difficult to establish students' understanding of adaptation is that the validated list of correct concepts about the topic of adaptation for this study (see Table 20, p. 77) contained six concepts important for a scientific understanding of adaptation, and only four of these concepts have frequencies of students' responses reported in the literature (see Table 6). Lastly, many more studies report frequencies of students' **unscientific ideas** about adaptation than their **scientific ideas** about adaptation. This presents a gap in the literature that this research helps to fill. Table 6 includes mainly studies that collected data at a single point in time. Where studies included both pre- and post-instruction studies, only the 'before-instruction' data is included in Table 6.

The first adaptation-related trend identified in the literature reviewed is how few students mention natural selection in their responses to questions about adaptation (Engel Clough & Wood-Robinson, 1985a). An understanding of natural selection is foundational to an understanding of adaptation, as it is the mechanism that drives the process of adaptation (Futuyma, 2009; Gregory, 2009). One possible reason for few students making mention of natural selection is that natural selection is poorly understood by students of all ages (Engel Clough & Wood-Robinson, 1985a). Table 6 shows that a poor understanding of natural selection is apparent in students from different countries and of different ages. Low levels of understanding of natural selection of students at all educational levels: primary school (Kelemen et al., 2014), high school (MacFadden, 2007; Tamir & Zohar, 1991) and college (Brumby, 1984). Coley & Tanner (2015) show that the mechanism of natural selection does not involve an innate way of thinking – something that students understand naturally as a result of what they observe in their natural environment. It is, rather, something that needs to be taught and learned, and sooner rather than later in a child's education (Kelemen et al., 2014). Kelemen et al. (2014) show that young students (seven and eight year-olds) can learn the basic concepts of natural selection that may aid understanding later in students' education.

The second trend in the pertinent literature is that few students mention variation when questioned about adaptation. Three studies looking at this concept (see Table 6) found that both high school and college students battled with the concept of variation (Bishop & Anderson, 1990; Moore et al., 2002; Yates & Marek, 2014). Variation is essential to the process of natural selection and a key factor in explaining adaptation (Freeman & Herron, 2007). Bishop and Anderson (1990) found that students with two or more years of biology experience were more likely to include the concept of variation in their responses (31% of the students), than students with only one to two years of biology study (16%), and students with less than one year, or no previous experience in biology (21%). Moore et al. (2002) found that their first-year university students routinely gave inappropriate responses to questions probing their understanding of variation in the peppered moth and the tuberculosis bacterium populations, with only 17% and 6% respectively providing correct scientific responses about the two populations. The literature suggests that the concept of variation tends to be ignored or inappropriately explained by high school and university students.

Table 6: Percentage of students with correct ideas about adaptation-related concepts

Author and year	Brumby (1984)	Engel Clough & Wood-Robinson (1985a)		Bishop & Anderson (1990)			Tamir & Zohar (1991)		Moore et al. (2002)		Macfadden (2007)	Nehm & Reilly (2007)	Kampourakis & Zogza (2008)			Keleman, et. al. (2014)				Yates and Marek (2014)	
Sample	medical students	12 - 16years		College students:			High school students		1st year university students		High school age or older	College students	14-15 years			5-6 years	7-8 years	5-6 years	7-8 years	Teachers & High school students in Oklahoma	
Differences within the sample	1st-year	e.g. caterpillar	e.g. Fox	years of prior biology education			Grade 10	Grade 12	Peppered moth	Tuberculosis	Interviews: 6 natural history museums	Combined understanding across two curricula	Elephant trunk length	Camouflage	Fox fur colour	Rapid natural selection		Gradual natural selection over many generations		Teachers	High school students
				0–1 years	1-2 years	2 or more															
Country	Australia	Britain		USA			Israel		RSA		USA	USA	Greece			USA				USA	
Sample size	32	84	83	110			16	12	126		380	201	98	98	98	28	33	16	16	35	536
Percentage of sample with an understanding of natural selection	10	12	10	0	5	3	7	33	41		30	3	2	2	39	0	0	0	13		
• variation among individuals in a population is essential to adaptation				21	16	31			17	6										91	39
• organisms with favourable adaptations generally survive longer and reproduce more successfully																		11	63		
• adaptation involves changing proportions of individuals with discrete traits				0	16	17															

The third trend noted in the literature reviewed is that few studies (only one was found) report on the inclusion of differential survival and reproduction rates in students' explanations of adaptation. Kelemen et al. (2014) note that 5 to 6 year-old students (11% of their sample) battled to understand the relationship between improved survival and reproduction and advantageous adaptations that lead to the improved fitness of the population, and therefore generally did not include it in their explanations of adaptation. However, 63% of their 7 to 8 year-old students mentioned differential survival and reproduction in their initial explanations of adaptation, albeit in rudimentary form.

The fourth trend is that few students recognised the importance of the changing frequencies of phenotypes in populations that are adapting. Only the study by Bishop and Anderson (1990, p. 424) included such data on students' correct explanations (the "changing proportion of individuals with discrete traits"). Prior to instruction, few students explained adaptation in this way: 0% of students with no prior biology tuition, 16% of students with between one and two years of prior biology tuition, and 17% of students with more than two years of prior biology experience.

I found four studies that investigated aspects of students' correct understanding before and after instruction (see Table 7, where B = before teaching and A = after being taught). However, very few results are reported, or reported as frequencies, and the success rate differed from study to study. A few interesting trends can be seen in Table 7.

Table 7:Studies investigating percentage of students with correct conceptions relating to adaptation, before and after instruction

Author and year	Bishop & Anderson (1990)						Jensen & Finley (1995)		Keleman, et. al. (2014)								Yates & Marek (2014)	
Age level	College students:						College students		5-6 years		7-8 years		5-6 years		7-8 years		Teachers & pupils in Oklahoma	
Differences within the sample	years of prior biology education								Rapid natural selection				Gradual natural selection over many generations				Students	
	0–1 year		1-2 years		>2 years													
Country	USA						USA		USA								USA	
Sample size	110						42		28		33		16		16		536	
B – before instruction; A – after instruction	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A
• have an understanding of natural selection	0	41	5	69	3	53			0	3	0	7	0	38	13	50		
• variation among individuals in a population is essential to adaptation	21	47	16	63	31	59	23	49									39	56
• organisms with favourable adaptations generally survive longer and reproduce more successfully	0	47	16	66	17	57							0/11	54/69	63	100		

Firstly, two studies report large improvements in students' correct responses after instruction on natural selection. Bishop and Anderson (1990) found that their students' ability to explain natural selection greatly improved, by as much as 63%, from pre- to post-instruction. Similarly, Kelemen et al. (2014) found that some children in their study, between 38% and 50% (see Table 7), aged between 5 and 8 years old, were able to learn about and comprehend the population-based logic of adaptation when it was presented in narrative form. Though some students in the Kelemen et al. (2014) study were able to learn the detail of natural selection and adaptation, the authors qualify their findings by advising that their study be used as evidence of initial learning to be built on and not evidence that students have arrived at a fully integrated scientific understanding of adaptation or natural selection. Based on their promising findings, Kelemen et al. conclude that:

> "Repeated, spaced instruction on gradually scaled-up versions of the logic of natural selection could ultimately place students in a better position to suppress competing intuitive explanations such that they could elaborate a richer, more abstract, and broadly applicable knowledge of this process". Kelemen et al. (2014, p. 901)

The second trend illustrated by Table 7 is that promising improvements in students' understanding of variation were reported among college-age students. Yates and Marek (2014), Bishop and Anderson (1990), and Jensen and Finley (1995) report improvements of 15% to 40% in students' explanations of variation in populations after instruction. Yates and Marek (2014) had a large sample (n = 536), taught by many different teachers in different schools, with no specific intervention. They report a 17% improvement in students' understanding of the importance of variation in adaptive change. Interestingly, they also report that students whose teachers were better qualified and who spent more time teaching evolution (11 to 15 hours more) displayed a better improvement in their overall evolution knowledge than did those whose teachers were less well qualified, suggesting that some teachers can have an impact on their students' understanding on some important concepts associated with adaptation. Bishop and Anderson (1990) made use of an intervention – laboratory experiments, problem solving sets, and transparencies and worksheets designed to highlight the inadequacy of the students' current conceptions – aimed at promoting conceptual change. Bishop and Anderson (1990) found that some (25% to 50%) of their college-level students' explanations after instruction included more scientific conceptions about the origin and survival of new traits, and the role of variation within populations and evolutionary change. Jensen and Finley (1995) also made use of an intervention, in the form of small-group laboratory exercises, facilitated by high achieving undergraduate biology majors, where students systematically worked through five principles of evolution (1. the nature of evolution; 2. Lamarckian ideas; 3. evidence opposing Lamarckian ideas; 4. Darwin's theory of evolution by natural selection; 5. problem solving using both Lamarckian and Darwinian ideas). They report that students' use of Darwinian conceptions, specifically the role and importance of variation in populations, increased by around 20%. A comparison between the three studies reveals that understanding adaptation-related concepts seems to improve through exposure to correct scientific knowledge of the topic, regardless of whether or not students are exposed to this through the normal teaching and learning process or a specific intervention.

2.4 UNSCIENTIFIC IDEAS ABOUT ADAPTATION

2.4.1 Single unscientific ideas

To establish the extent of students' unscientific ideas about the topic of 'adaptation', I located and reviewed 22 studies, summarised in Table 8. In the table, these studies have been arranged by year of publication, starting with the oldest (Jungwirth, 1975) and ending with the most recent (Shtulman et al., 2016). The samples in each of the studies varied considerably. For example, Kampourakis and Zogza (2008) included students as young as five years of age in their sample and Yates and Marek (2013, 2014) included teachers in their sample. The studies reviewed in this section also differed in terms of country of origin, with research emanating from eight different countries. While some studies used the same or similar instruments to gather the data (e.g. Engel Clough & Wood-Robinson, 1985a, 1985b), most of the studies used instruments and questions unique to their study. This is important because the frequencies of unscientific ideas have been shown to be influenced by the context of the question being asked (Engel Clough & Wood-Robinson, 1985a). Two studies included research on students' unscientific ideas about adaptation-related concepts before and after instruction (Settlage, 1994; Yates & Marek, 2014). Interestingly, Settlage (1994) reports a significant decline in the percentage of misconceptions in the sample after instruction, while Yates and Marek (2014) report that students' unscientific ideas were approximately the same before and after instruction for two unscientific ideas, while misconceptions for a third unscientific idea increased from pre- to post-instruction.

Two main trends associated with unscientific ideas about adaptation could be found in the research reviewed in Table 8. Firstly, many of the misconceptions about adaptation could be attributed to a lack of understanding of natural selection. Engel Clough and Wood-Robinson (1985b) and Settlage (1994) found that the majority of students in their studies (>90%) did not understand natural selection and claim that consequently they did not understand adaptation. Kelemen et al. (2014) and Settlage (1994) are of the opinion that the lack of understanding of natural selection is a result of the fact that students are simply not taught the topic until late high school. Lastly, unscientific ideas appear to be informed by three common unscientific ways of thinking, anthropomorphism, teleology, and Lamarckism. Need-based reasoning (teleology), desire-based reasoning (implying anthropomorphism) and the Lamarckian idea of use and disuse inform the four most frequent unscientific ideas identified in the literature (see Table 8). More specifically, students struggle with goal-directed and purpose-related (teleological) thinking about natural objects (Jungwirth, 1975; and Kampourakis, Palaiokrassa, Papadopoulou, Pavlidi, & Argyropoulou, 2012). As discussed in section 2.4.3 (p. 36), teleological thinking is an innate human tendency displayed by children and adults, and may come from human experiences linked to intentional agents of change (Kampourakis & Zogza, 2008; Kelemen, 1999).

Both Kelemen et al. (2014) and Shtulman et al. (2016) found that it is possible for some young students to understand the basic concept of natural selection and that this understanding of natural selection improved their understanding of adaptation. This finding is of particular relevance to my study because by the time South African students are in Grade 12 (where they are taught natural selection for the first time) they already have many misconceptions about biological adaptation, which is taught in various grades to younger scholars in South Africa. This could perhaps be prevented if students are exposed to the basic principles of natural selection in earlier grades, before or while learning about adaptation, as advised by Kelemen et al. (2014) and Shtulman et al. (2016).

Each unscientific idea identified in the literature is discussed in more detail here and after Table 8.

- **Organisms adapt because they need to**

  Explaining adaptation in terms of an organism's need was the most frequent unscientific idea in the literature reviewed and summarised in Table 8, and appears to be prevalent among students of all ages and from many different countries.

Table 8: Unscientific ideas about adaptation, and their frequency (%), as identified in research literature

Author and Year	Jungwirth (1975)			Brumby (1984)	Engel Clough & Wood-Robinson (1985)		Engel Clough & Wood-Robinson (1985)			Bishop & Anderson (1990)	Tamir and Zohar (1991)				Settlage (1994)		Ramorogo & Wood-Robinson (1995)			Jensen & Finley (1995)	Jensen & Finley (1996)				Moore et al. (2002)			MacFadden (2007)	Nehm & Reilly (2007)	Nehm and Schonfeld (2007)	Kampourakis and Zogza (2008)					Cunningham & Wescott (2009)	Kampourakis, Pavlidi, Papadopoulou & Palaiokrassa (2012)			Legare, Lane & Evans (2013)	Yates & Marek (2013)	Yates & Marek (2014)			Keskin & Kose (2015)	Robertson (2015)	Shtulman, Neal & Linquist (2016)
Sample	Year 10	Year 12 & 13	3rd-year university	1st-year medical students	12 to 16 year-olds		12 to 16 year-olds			College students	Grade 10		Grade 12		High school students		Primary and high school students			College students	College Students				1st year univ. students			Visitors at natural history museums	College students	Student teachers	5 to 12 year-olds					Undergraduate students	Pre-school	1st Grade	2nd Grade	5 - 12-year-olds	Teachers	Teachers	High school students in Oklahoma		Pre-service teachers	Grade 8 students	Ages 4 - 12
							Tails	Athletes	Gardeners								Tails	Athletes	Gardeners						Peppered moth 1	TB	Peppered moth 2				Dogs and wolves	Elephant trunk length	Camouflage	Fox fur colour	Cells												
Country	Israel			Australia	Britain		Britain			USA	Israel				USA		Botswana			USA	USA				South Africa			USA	USA	USA	Greece					USA	Greece			USA	USA	USA	USA		Turkey	RSA	USA
Sample size	220	129	48	150	84	83	84			110	16		12		50		300			42	22	30	20	32	98			380	98	44	98					547	74	153	149	98	76	35	536		117	12	98
											Flora	Fauna	Flora	Fauna	Pre	Post																											B	A			
Organisms adapt because they need to					-	49				✓					70	24												✓	✓		22	70	52	30	63	66	41	46	39	✓	22	10	40	36	72	18	✓
Individual organisms adapt	15	4	2	60	✓	✓					25	81	33	42	✓					✓								✓		25										✓	45	45	83	77	47	18	✓
Adaptations are gained or lost through use and disuse				72						✓			44	10	22	5	✓			15	19				11	18			✓	25	-	0	16	0	-												
Organisms try, wish, or strive to adapt	53	47	38		8	16					25	81	33	42											22	31	19		✓							8									67	58	
Acquired adaptations get passed on to the next generation							19	13	2								17	31	17		15	19	11	18																							
Environmental change causes adaptation																															-	7	5	3	-	78					90						
Only organisms with the best adaptations survive (survival of the fittest).																																				64					41	41	63	69	61		
Organisms develop adaptations in order to perform certain functions (purpose).	69	60	41							✓																																					
Organisms try to move to a more favourable environment					19	1																																								18	

✓ Mentioned as a problem in the study but no frequency given

\- indicates no data provided

Of the 22 studies reviewed, 15 point out that at least some students believed that organisms change because ‘they need to’, with frequencies ranging from 10% to 72% of the samples investigated: for example, the belief that polar bears have evolved thick coats because they needed to survive harsh winters.

According to this belief, the existence of the trait is explained by the organism’s realisation that it will die if it does not have the necessary trait. Explaining adaptations according to ‘need’ is an indication of teleological thinking (discussed in more detail in the next bullet) and anthropomorphic thinking (see Section 2.4.3 for further discussion). In reality though, ‘need’ has nothing to do with adaptation. Natural selection, the mechanism that leads to adaptation, leads to improved survival and reproduction of some organisms in the population that have advantageous traits.

- **Organisms have structures in order to perform certain functions**

  This unscientific idea is closely related to the previous unscientific idea, as an organism’s perceived ‘need’ to adapt is often closely linked to the perception of the organism’s need to survive. While this unscientific idea was mentioned in comparatively few studies in Table 8 (four of the 22 studies), this unscientific idea is problematic to learning. Jungwirth (1975) found it to be a common problem in his study (69% of the Grade 10 students, 61% of the Grade 12 students, and 41% of the 3rd year university students). At the centre of this misconception is the teleological belief that the reason for the traits evolving is to perform an important function for the organism (Kelemen, 2011). This idea highlights a particular problem with teleological thinking, the erroneous belief that the perceived role played by the trait explains the cause of the trait (Kelemen, 2011). In reality though, the origin of new traits in populations of organisms is either random mutation or immigration of individuals from outside the original population, thus bring in new alleles. This process is not intentional or deliberate, nor does it occur to improve an organism’s fitness to an environment. Mutations are errors in replication that happen to have lead to new variations in the population, whilst immigration is a chance happening.

- **Individual organisms adapt**

  The erroneous idea that individual organisms adapt is a common problem among students of all ages (see Table 8, data row 2). Thirteen of the 22 studies reviewed report that between 2% (university students) and 83% (high school students) held this unscientific idea. The percentage of students who hold this misconception appears to decrease with age. Lower frequencies of this unscientific idea occur among university-level students and teachers (Jungwirth, 1975; Keskin & Kose, 2015; Yates & Marek, 2014) and higher frequencies of this unscientific idea occur among samples of high school students (Jungwirth, 1975; Tamir & Zohar, 1991; Yates & Marek, 2014). The idea that individual organisms adapt may be linked to other (non-evolutionary) definitions of adaptation, such as the immediate physiological responses that occur as an organism responds to its environment (discussed in section 2.3, starting on page 19). Adaptation does not occur to individual organisms (which cannot change their genetic makeup) but to populations of organisms over many generations (Gregory, 2009; van Dijk & Reydon, 2010).

- **Organisms improve structures through use, or lose structures through disuse**

  The idea that organisms gain or lose traits through the ‘use or disuse’ of the trait was the third most frequent unscientific idea in the literature reviewed, with 11 of the 22 studies having identified students giving such answers. The range of students from each sample varies considerably, with

72% of the first-year medical students in the Brumby study (Brumby, 1984) to 5% of the high school students in the Settlage study (Settlage, 1994). The presence or absence of certain traits in a population is not dependent on ‘use or disuse’, but rather to what degree a trait is advantageous in terms of survival and reproduction for the organisms that bear it.

- **Organisms try, wish, or strive to adapt**

  The idea that adaptation is caused intentionally by living organisms was identified in seven of the 22 articles reviewed in this study with frequencies of between 8% and 81% within the samples. While the occurrence of this misconception appears to be more frequent in high school student samples, Keskin and Kose (2015) worryingly found this to be a common unscientific idea (67%) among pre-service teachers. While ascribing to animals human levels of intentionality is a common idea in non-scientists, scientists understand that non-human organisms cannot control their genotype or their phenotype and do not have the ability to think and plan. The anthropomorphic unscientific way of thinking that ascribes human abilities and cognitive abilities to non-human objects, informs this misconception.

- **Inheritance of acquired ‘adaptations’**

  Four of the 22 articles reviewed for this study identified this unscientific idea, with 2% to 32% of the students in their samples. There does not appear to be any noticeable difference between the frequency of this misconception among college students or primary and high school students. Engel Clough and Wood-Robinson (1985a) and Ramorogo and Wood-Robinson (1995) report differences in the frequency of students holding this unscientific idea in samples in Britain (2% - 19%) and Botswana (17% - 31%), depending on the scenario used in the questions. Physical changes that occur in response to training or changes in the environment (sun/ moon etc.) are not inherited by the offspring because they only affect somatic cells and not the gametes (Gregory, 2009).

- **Changes in the environment cause adaptation**

  The exact role that the environment plays in adaptation is a source of confusion for students and teachers alike (Bishop & Anderson, 1990). Three of the 22 articles reviewed in this study found this unscientific idea present in their sample. One study found that this was an uncommon unscientific idea among young students aged between five and 12 (Kampourakis & Zogza, 2008). However, two other studies found that more than 70% of undergraduate students and teachers held this unscientific idea (Cunningham & Wescott, 2009; Yates & Marek, 2013). Bishop and Anderson (1990) point out that some students think that adaptation occurs only when environmental changes occur. Scientists understand that the environment does not cause or initiate adaptation. Bearing in mind that genetic variation in a population means that organisms with a range of adaptedness exist in most populations, when environmental change occurs organisms that previously had less favourable adaptations in the environment may suddenly have a survival and reproductive advantage over others causing those traits to become more frequent in the population over many generations, in the new environmental conditions. This is the result of natural selection in the new conditions, but was not caused by the change. It will happen only if favourable alleles happen to be present, or new mutations develop by chance.

- **Organisms try to move to a more favourable environment**

  A small number of students think that if organisms are not happy or cannot survive in their current environment they will move to another. Engel Clough and Wood-Robinson (1985b) found that 19%

of the 84 students from three schools in Britain thought that organisms respond to changes in their environment by seeking out a more favourable one. Similarly, Robertson (2015) found that 18% of his Grade 8 South African students thought that organisms would move to a more favourable environment when detrimental environmental changes occurred. This erroneous idea seems anthropomorphic as it implies that organisms are aware that their environment is unsuitable, or they are discontent in their environment and therefore seek to move to another, as humans might do.

- **Only the strongest organisms in an environment survive**

  A relatively high proportion of students, and some teachers, misinterpret the word ‘fittest’ and believe it to mean that the most physically fit will survive. Four of the 22 articles reviewed for this study report this unscientific idea, with between 41% and 69% of students in various studies believing it. van Dijk & Reydon (2010) point out that natural selection does not ensure the ‘survival of the fittest’: it filters out those with the least favourable traits and leaves the rest. Interestingly, Yates and Marek (2014) report a small increase in frequency of this unscientific idea from pre-evolution instruction (63% of the students) to post-evolution instruction (69%) in their study of 536 high school students in Oklahoma.

2.4.2 Alternative frameworks about adaptation

In everyday English a ‘framework’ is defined as either “an essential supporting structure of a building, vehicle, or object” or as a “basic structure underlying a system, concept, or text” (Oxford University Press, 2017). The key words in these definitions are ‘support’ and ‘structure’, both words suggesting that a framework provides shape to, and support for, something. A ‘mental’ framework develops as students think and seek explanations for events in their experience (McClelland, 1984). The term ‘schemata’ is often used in education circles to refer to such mental frameworks. Schemata are “conceptual structures and processes which (sic) enable human beings to store perceptual and conceptual information about the world and make interpretations of events” around them (Derfer, 1995, n.p.). They can be likened to a lens that helps those looking through it interpret the world around them. The development of schemata is bidirectional in the sense that individuals interpret the information being received, which often involves changes in the structure of the schema itself in order to accommodate the new information. In this sense, schemata are dynamic structures that are constantly changing as students are exposed to different stimuli in the world (Derfer, 1995; Greca & Moreira, 2000). Kelemen et al. (2014) point out that children are natural explanation seekers who tend to organise their knowledge into schemata. While McClelland (1984) agrees that students theorise and develop schema, he is sceptical of the level and pervasiveness of the theory-making hypothesis, pointing out that students tend only to exert thoughtful effort about things that matter to them. One of the challenges for science education is to promote the development of a coherent schema that aids science learning and understanding, rather than hinders it.

Schemata constructed by students do not always fit in with conceptual models in science. Such models are developed by researchers, teachers, or engineers as they study the natural world and construct external representations of a phenomenon (Greca & Moreira, 2000). Driver (1981) notes that the built-up expectations, beliefs or schemata that students develop about the world around them do not always match the scientific conceptual models that the teacher would like them to develop. Greca and Moreira (2000) state that students may pull out elements that they consider relevant from what they are being taught, and relate them to what they already know, but in ways that are not scientific. Alternative frameworks are problematic to the extent that they inhibit or prevent further learning (Freyberg & Osborne, 1985). In this study, there are four relevant alternative frameworks about the topic of adaptation.

The ‘evolution on demand’ alternative framework

The unscientific framework known as ‘evolution on demand’ places individual organisms and their needs at the forefront of evolutionary change. The phrase ‘evolution on demand’ encapsulates students’ tendency to view the organism as the agent of change, as opposed to some external force (Moore et al., 2002). Students who explain adaptation as an ‘ability’ that an organism has, as something an organism ‘chooses’ to do, or because of some ‘need’ that an organism has are using language associated with the ‘evolution on demand’ framework (Jensen & Finley, 1995). The ‘evolution on demand’ framework incorporates desire-based reasoning that explains the presence of an adaptation in terms of an organisms’ ‘desire’ or ‘want’ for the trait, or ‘need-based’ reasoning which explains the existence of certain traits in terms of an organisms’ need for the trait (Legare et al., 2013; Shtulman et al., 2016). The unscientific ideas in this framework occur when human reasoning and behaviour patterns (anthropomorphism) are credited to objects or organisms, as if they can apply them for a particular purpose or reason (teleology), often related to survival. Individual unscientific ideas associated with this framework include: 1) the environment causes organisms to adapt, 2) this occurs because the organisms need the adaptation in order to survive, 3) organisms are aware of their need to change, 4) the organism decides to change because the new adaptations are favourable, 5) individual organisms adapt, 6) this happens in an individual organism’s lifetime.

The ‘survival of the fittest’ alternative framework

The phrase ‘survival of the fittest’, first coined by Herbert Spencer, was used by Darwin in his fifth edition of ‘On the Origin of Species’ as a synonym for natural selection (Rees, 2007; van Dijk & Reydon, 2010). This was an unfortunate decision for three reasons. Firstly, the phrase became associated with the social Darwinism of the Nazis and their persecution of the Jews (and what Nazi’s considered to be other ‘inferior’ races or groups) during World War 2 (Futuyma, 2009). Secondly, the words ‘fit’ or ‘fittest’ are ambiguous. In everyday English, ‘fitness’ refers to the health, strength, endurance, intelligence or speed of an organism (Bishop & Anderson, 1990). In evolutionary biology, however, fitness refers to an organism’s ability to produce viable offspring (Bishop & Anderson, 1990; van Dijk & Reydon, 2010). Finally, “it places undue emphasis on survival without taking reproduction into consideration” (Pobiner, 2016). Survival is only of value to a population if it leads to more progeny that carry advantageous traits.

Six erroneous ideas have been identified in this alternative framework by various authors (Gregory, 2009; Pobiner, 2016; Tshuma & Sanders, 2015). Individual misconceptions are pointed out in the ‘unscientific idea’ column and then corrected in the ‘explanation’ column of Table 9.

Table 9: Unscientific ideas associated with the 'survival of the fittest' alternative framework

Unscientific idea	Explanation
Those with favourable traits WILL survive	While organisms with advantageous traits are likely to survive longer than those that do not have the trait, survival is not a guarantee. Organisms with advantageous traits may die from disease, predation, exposure to the elements and pollution, in much the same way as those that do not have the advantageous trait.
The less well adapted organisms WILL die or become extinct	Both 'fit' and 'less fit' organisms will continue to live together in a population (Gregory, 2009). The 'less fit' may decrease in number in the population but will not necessarily die.
Only organisms with advantageous traits will reproduce and the unfit will not reproduce	Organisms that do not have the 'favourable' trait in question will still reproduce. The difference between them and the more favourably endowed is reproductive capacity (Gregory, 2009). Organisms with advantageous traits are likely to reproduce more successfully than those that do not, so that the proportion of individuals with the favourable trait in a population will increase.
ALL offspring will inherit the favourable traits	There are too many variables at play in the sexual reproduction of organisms to suggest that all of the offspring of two favourably endowed parents will have the favourable trait. It will be affected by factors such as dominance of the relevant genes, and homo- and hetero-zygosity of chromosome pairs. Whilst the frequency of the trait in the offspring of two 'fit' organisms may increase, there is no guarantee that all of the offspring will inherit the trait (Campbell et al., 2015).
Survival of the fittest means that the physically strong / physically fit survive	Physically strong organisms can die from disease or predation. Physical strength or fitness is of no evolutionary value to a population if it does not affect reproductive success. Organisms may be physically less strong, but still survive, especially if they have other 'favourable' traits.

The Lamarckian alternative framework

While Jean-Baptiste Lamarck is regarded as a key contributor in the development of the evolutionary theory, he is remembered for his incorrect explanations of the mechanism of evolution rather than his overall contribution (Campbell et al., 2015). Lamarck's explanation of the mechanism of evolution contained two main principles, 'use and disuse' by individuals and the 'inheritance of acquired characteristics', both of which have been shown to be unscientific (Campbell et al., 2015; Gregory, 2009). The first of Lamarck's ideas (the 'use and disuse' notion, see Table 8, p. 30), is that parts of organisms that are used frequently grow or get progressively stronger, while those that are not used get progressively smaller and eventually disappear (Campbell et al., 2015; González Galli & Meinardi, 2011; Gregory, 2009). The second principle concerns the 'inheritance of acquired characteristics' (see Table 8, p. 30) or "soft inheritance" (Gregory, 2009b, p. 169). This is the idea that the adaptations that develop during an organism's lifetime are passed on to their offspring (Campbell et al., 2015). For example, Lamarck reasoned that giraffes at one time stretched their necks to reach food on higher branches and that with each passing generation the neck got progressively longer (Gregory, 2009). Such ideas were common both before and during Darwin's lifetime, and are still common today (Bishop & Anderson, 1990; Cunningham & Wescott, 2009; Wood-Robinson, 1994). These erroneous Lamarckian ideas of 'use and disuse' and 'inheritance of acquired characteristics' have a close conceptual association that can inhibit learning, and together form a problematic alternative framework.

Essentialism as an alternative framework

Of all the alternative frameworks about evolution that exist, essentialism is probably the oldest and most intuitively held by young children (Mayr, 1988; Shtulman, 2006). Essentialism is the belief that all organisms of a species have an immutable essence which dictates the characteristics of organisms in a population (Gregory, 2009; Pobiner, 2016). In other words, all organisms in a population are the same because they have the same essence. Shtulman (2006, p. 171) explains "…that individuals of all ages and cultures assume that a species' outward appearance and behaviour are determined by a kind of hidden causal power or "essence"". Shtulman (2006, p. 171) goes on to point out that "human beings tend to essentialize biological kinds and essentialism is incompatible with natural selection". The incompatibility of essentialism with natural selection is problematic to students' understanding of evolution, generally, and adaptation, specifically. With regards to adaptation, a common essentialist idea is that a whole species can adapt (at the same time) in response to an environmental change (Gregory, 2009; Shtulman, 2006). This is contrary to the scientific understanding that differential survival and reproduction of individuals with different variations in a population leads to changes in the frequency of specific traits in that particular population (Futuyma, 2009; Gregory, 2009).

2.4.3 Unscientific teleological and anthropomorphic ways of thinking

While both anthropomorphism and teleology are defined in Chapter 1 (section 1.4.3, p. 9), and discussed briefly again in section 2.4.2 starting on page 33, both these unscientific ways of thinking are elaborated on here, in light of their association with, and apparent influence on, certain unscientific ideas and alternative frameworks.

Anthropomorphism

Anthropomorphism is the tendency to ascribe human-like behaviour patterns or ways of thinking to non-human entities (Wynne, 2007). Anthropomorphic thinking, when explaining adaptation, inhibits a scientific understanding of the origin of adaptations. Students tend to credit adaptive progress in terms of desire or thoughtful intentions of adapting organisms rather than the causal mechanism of natural selection as if they can reason like humans (Coley & Tanner, 2012; Gregory, 2009; Legare et al., 2013). Instead of providing causal explanations for the existence of certain traits, anthropomorphic thinking credits the organism as being the agent of change. For example, the unscientific ideas that peppered moths *realise* (emphasis added) that the tree bark in their environment is darker and therefore *choose* to adapt in order to survive, suggests a human-like awareness by the moth, and an intentional decision to change. It also highlights the close relationship between anthropomorphism and teleology by linking an organism's desire with an associated reason or purpose to adapt.

Teleology

Teleology is the tendency to explain the existence or presence of natural phenomena with reference to purpose or a goal-directed end, like survival (Coley & Tanner, 2015; Yip, 2009). Cognitive psychologists argue that teleological reasoning is a common intuitive way of thinking, understood to be an explanatory default for every person throughout their lives (Kelemen & Rosset, 2009; Trommler et al., 2018). Knowledge about the true cause of adaptation (evolution) may suppress teleological reasoning but it never replaces it (Kelemen & Rosset, 2009). Teleological reasoning may surface even in people with high scientific literacy when their processing capacity is diminished (e.g. dementia) or when giving answers under time pressure (Kelemen & Rosset, 2009; Trommler et al., 2018). Teleological reasoning is common among people of all ages and is problematic to understanding the topic of adaptation correctly, for a number of reasons. Firstly, there is a tendency for people to understand teleological phrases literally and not metaphorically, which is how they tend to be used (Jungwirth, 1975). A number of authors note that teleological language is a commonly used form of metaphorical language that can be useful in the teaching and learning evolution (Tamir & Zohar, 1991; van Dijk & Reydon, 2010; Yip, 2009). However, it also has the potential to confuse students (Anderson et al., 2002), especially when used with reference to adaptation (Mayr, 1992). Secondly, teleology is closely connected to anthropomorphism (Mayr, 1992; Tamir & Zohar, 1991) and may cause, or be symptomatic of, the 'evolution on demand' alternative framework (see section 2.4.2). In this regard, two types of teleology can be distinguished, one that is independent of anthropomorphism, and one that is closely aligned with it (Tamir & Zohar, 1991). The latter is regarded as being more problematic to an understanidng of natural selection than the former (González Galli & Meinardi, 2011). Thirdly, students tend to explain phenomena in terms of need or purpose rather than by the causal evolutionary mechanism of natural selection (González Galli & Meinardi, 2011). Mayr (2014) argues that an adaptive characteristic is the result of the process of natural selection, and is not needs satisfying or goal-seeking. Settlage (1994) and Cunningham and Wescott (2009) found that 70% and 66% of high school and undergraduate students, respectively, in their studies believed the erroneous teleological idea that organisms adapt because they need to.

Anthropomorphism and teleology are closely related in two ways. Teleological statements have anthropomorphic implications attached (Bartov, 1981; Mayr, 1992) and anthropomorphic statements are often goal- or purpose-driven (Bartov, 1981; Sanders, 2014b; Tamir & Zohar, 1991). For example, the erroneous idea that 'a peppered moth adapts in order to survive' makes use of both teleological and anthropomorphic reasoning resulting in scientifically incorrect explanations of **how** peppered moths adapt. The phrase 'a peppered moth adapts' implies the human act of choosing and the phrase 'in order to survive' assumes some intelligence behind the purposeful intention to survive, as well as predictive thinking of something yet to come. While students may use anthropomorphism and teleology intuitively (Coley & Tanner, 2015; Tamir & Zohar, 1991), teachers need to be careful when using such language lest they confirm unscientific ideas in students' thinking (Mayr, 1992).

Concluding remarks about teleology and anthropomorphism

The appropriateness of the use of anthropomorphic and teleological language when explaining evolutionary concepts is fiercely debated. Many authors argue that anthropomorphism and teleology are impossible to eliminate such wording from the language used by teachers when explaining science (González Galli & Meinardi, 2011; Tamir & Zohar, 1991; Yip, 2009). Others suggest that teleology, specifically, has heuristic value in that it is a useful explanatory tool that many teachers and lecturers make use of in their instructions and that students easily understand and relate to (González Galli & Meinardi, 2011; Southerland et al., 2001; Tamir & Zohar, 1991; Trommler et al., 2018).

While anthropomorphic and teleological explanations may be useful in teaching, they are problematic when talking about the topic of adaptation, for a number of reasons. Firstly, anthropomorphic and teleological ideas are inherent in the everyday meaning of the word 'adaptation' and may prevent students from understanding the correct scientific meaning of adaptation. The everyday meaning of adaptation is problematic because it implies sudden or short term changes that individual organisms are consciously aware of and in control of strategies to help them to survive. Teachers need to be careful how they phrase their explanations so as not to imply any of the aforementioned unscientific ideas that may lead students to form incorrect ideas about adaptation. Secondly, students naturally tend towards anthropomorphic and teleological reasoning (Coley & Tanner, 2015; Kampourakis & Zogza, 2008; Trommler et al., 2018) which is associated with the idea that organisms adapt on demand when they want or need to. The ‘evolution on demand’ alternative framework contains a number of unscientific ideas, many of which contain anthropomorphic and teleological reasoning.

2.5 POTENTIAL SOURCES OF UNSCIENTIFIC IDEAS ABOUT EVOLUTION

The literature points out that students have an innate tendency to think about adaptation in unscientific ways (e.g. Kelemen, 2012; Legare et al., 2013; Shtulman et al., 2016). However, a number of external factors may contribute to, and even reinforce, existing misconceptions. This section highlights some of those potential sources pointed out in the literature. These sources can be divided into two broad categories based on where students are likely to have encountered them, namely, out-of-school sources and in-school sources. The discussion of potential sources of unscientific ideas below is not exhaustive, and merely describes the most likely causes of unscientific ideas among students.

2.5.1 Out-of-school sources of unscientific ideas about evolution

Out-of-school sources of unscientific ideas are likely to have an influence on students’ understanding of science phenomena before they are formally taught in class (Engel Clough and Wood-Robinson, 1985a). Out-of-school sources include parents, family members, community members, peers etc.; multivalent terms; and various forms of media.

- **Parents / family members / community members/ peers etc.**

  Parents have an important role to play in helping children understand their social, cultural and natural environments. Sometimes cultural beliefs clash with scientific knowledge, and parents, if they are aware of the conflict (and many are not), may need to make a choice about whether or not to compromise teaching their child about a scientific concept to teach them to uphold religious or cultural norms even if this teaching is unscientific (Ramorogo & Wood-Robinson, 1995). The latter can be a barrier to learning science (Jegede, 1991). For example, parents in Botswana, in order to avoid discussing sex – a cultural taboo – often tell their young children that babies are bought from a hospital or picked up from the horns of an antelope (Ramorogo & Wood-Robinson, 1995). Parents are also, generally, the first people children depend on to explain scientific phenomena to them, including evolution-related concepts. Teaching children about evolution topics may be problematic for some conservative religious families (Sanders & Makotsa, 2016), whilst other parents may not be able to explain evolution in an effective, coherent manner because they themselves have not learned about it. Legare, Lane, and Evans (2013) point out that parents are often called upon to translate evolutionary language into simpler language for their children to understand. While this is not problematic in and of itself, unscientific explanations that make use of anthropomorphic and teleological language can mislead students and promote the development of alternative frameworks about evolution and adaptation (Legare et al., 2013).

- **The media**
  Media refers to “The main means of mass communication (broadcasting, publishing and the internet) regarded collectively” (Oxford University Press, 2017) and includes such forms as newspapers, television, magazines, the internet, books, and the so-called ‘social media’. Students are often in contact with a variety of media forms before they come into the classroom, and certainly before learning about evolution at school. Engel Clough and Wood-Robinson (1985b, p. 126) noted 30 years ago that evolution, “is well covered by the media, particularly television, and so it is likely that

children will be developing their own ideas long before the subject is covered in school science". Similarly, Zohar and Ginossar (1998) note that the home and the school are no longer the only "regulators of childhood development" (Postman, 1982, cited by Zohar and Ginossar, 1998, p. 682) because children are learning about the world around them through their (almost constant) connection to varying forms of media. The media also have their own agenda when depicting scientific phenomena. Media often make use of visual and auditory imagery to dramatise biological phenomena so that they become more appealing to the senses. This includes the frequent use of anthropomorphic and teleological wording (Zohar & Ginossar, 1998). While adaptation is only a small aspect of evolution, many children might be influenced by what is said about adaptation in the media (see Table 10 for an example). Unscientific ideas about adaptation in the media can be found in a popular children's movie, "Happy Feet 2" (Miller, Eck, Coleman, & Livingston, 2011).

Table 10: Common misconceptions about adaptation found in a popular children's movie

Extract	Extract of the conversation	Unscientific ideas
1	This is our moment, Bill. Okay. Adapt or die, my friend. Adapt? There's no telling what we might become Fine. Be a plankton muncher all your life. But that's what we are. We're herbivores. We eat veggies. Right. So everyone else can eat us. Well, I am not prepared to be on the menu any longer. Where you going? I'm moving up the food chain. The food chain? I'm gonna go chew on something that has a face!	- Organisms that don't adapt, die. - Individual organisms adapt. - This occurs within their lifetime. - Conscious awareness of danger or predators. - Organisms choose to adapt.
2	You can't stalk. You're a krill. We've got to evolve, Bill. Evolve? Just like that? It's taken us millions of years just to get this far. Watch and learn, Billy-boy. I'm about to naturally select.	- Organisms need to evolve (in order to survive) - Organisms choose to evolve. - This occurs within their lifetime.
3	We could start a little swarm. We're both males. We'll adopt. You adopt, I'll adapt. I've got slaughtering to do. Fine, that's just fine! Off you go then. Quench your blood lust.	- Individuals adapt. - They are consciously aware of the need to adapt. - Organisms choose to adapt.

On at least three occasions in the movie, a discussion between two krill, named Bill and Will, contains common unscientific ideas about adaptation and evolution. The underlined sections in Table 10 contain unscientific ideas about biological adaptation, and strongly reflect anthropomorphic and teleological thinking. The extracts illustrate some common unscientific ideas in the media that may influence how children think about adaptation.

- **Unscientific ways of thinking**

  Unscientific ways of thinking include anthropomorphism, teleology, essentialism, and Lamarckism. These ways of thinking may lead to development of misconceptions associated with alternative frameworks that may hinder science learning. See sections 2.4.2 (p. 33) and 2.4.3 (p. 36).

- **Multivalent terms**

  As discussed in Section 2.3.1, the word adaptation has a variety of meanings depending on the context within which it is used. The meaning of adaptation in science is very different to its meaning in everyday language. If the meanings are not distinguished from one another, students may have difficulty understanding what adaptation means in science. This may contribute to unscientific ideas about adaptation in the biology classroom.

2.5.2 School-based sources of unscientific ideas about evolution

Students don’t only learn unscientific ideas from out-of-school sources, but also from teachers and textbooks within the educational environment.

- **Textbooks**

  Textbooks have been shown to contain actual misconceptions as well as latent errors that may lead students to develop misconceptions. Actual errors are scientifically incorrect facts that are found in textbooks (Tshuma & Sanders, 2015). Latent problems occur when information is poorly worded or incomplete and may lead students to draw the wrong conclusions about evolutionary phenomena (Tshuma & Sanders, 2015). Actual scientific errors (Rees, 2007) and latent errors in the form of ambiguous and misleading explanations (Linhart, 1997) have been found in textbooks around the world. In South Africa, textbooks have been shown to contain both actual errors and latent problems about the topic of evolution (Sanders & Makotsa, 2016; Tshuma, 2016). These errors and problems in textbooks negatively impact both teaching and learning (Aleixandre & Jiménez Aleixandre, 1994; Hutchinson & Torres, 1994).

- **Teachers**

  Teachers can be a source of unscientific ideas about evolution in the science classroom, as many have unscientific ideas about evolution (Yates & Marek, 2013, 2014). Yates and Marek (2013, 2014) found that students were four times more likely to increase the number of misconceptions after learning about evolution if their teachers had poor content knowledge than those whose teacher’s content knowledge of evolution was excellent. BouJaoude, Wiles, Asghar, and Alters (2011) found that evolution was poorly covered or not covered at all in 49% of Egyptian and Lebanese high school classes in their study, because of the strong cultural and religious reservations to it in those societies. The many cultural problems associated with teaching evolution, human evolution specifically, “…leads some teachers to deemphasize evolution or avoid teaching it altogether” (Pobiner, 2016, p. 239). Many South African teachers ignored or avoided the topic of evolution when it was first introduced in 2008 (Sanders & Ngxola, 2009). Other South African teachers admitted that their content knowledge was poor and that they did not know how to teach the topic (Sanders & Ngxola, 2009). While much has changed since 2008, when evolution was first introduced into the Life Sciences curriculum in South Africa, lingering negative sentiment toward evolution or poor teacher content knowledge may still negatively influence the learning of evolution in South African classrooms. Similar problems occur in other parts of the world. For example, research conducted in Spain by Jiménez Aleixandre (1994) found that, “some teachers seem to share pupils’ difficulties when trying to interpret instances of biological change, which is a cause for serious concern”.

2.6 CONCLUDING REMARKS

Although I have not titled this chapter ‘literature review’, it is a literature-based conceptual framework organised around four central topics and their associated links. While much research has been conducted, and journal articles written, about the topic of evolution in education, comparatively few research articles focus specifically on the topic of adaptation in education. Of the studies that focus on adaptation, most (about 22 articles) report on the extent of students’ **misconceptions and unscientific ideas** about adaptation, and only ten have any useable research on the extent of students’ **scientific ideas** about adaptation. Of those that do have some research, only one or two adaptation-related concepts are reported on. This leaves at least five adaptation-related concepts, important to a scientific understanding of adaptation for which there is no research of students’ ideas. This stands in contrast to the many textbooks (e.g. Ridley, 2004), textbook chapters (e.g. Futuyma, 2009) and journal articles devoted to the topic of adaptation in the scientific literature (Bock, 1980; Gardner & Grafen, 2009; Gould & Lloyd, 1999; Williams, 1966).

Part of the challenge of developing the conceptual framework was identifying the factors that have an impact on students’ understanding of the topic of adaptation. The literature pointed out that an understanding of natural selection is central to an understanding of the concept of adaptation because natural selection is the mechanism by which adaptation occurs. This link is seldom made in the classroom, in textbooks, or in curriculum statements (syllabi). The problem of the multiple meanings of adaptation in science also appears to a serious obstacle to an understanding of evolutionary adaptation.

Chapter 3

The research design and methods

This chapter outlines the research design and methodological framework for the research project. It provides a detailed description so that readers may conceptualise the overall research plan, which includes the research questions, the selection of the sample, the sorts of instruments used, the ethics protocol followed, the procedures for organising and analysing the data, and measures for maintaining research rigour. The research question with its more specific sub-questions, outlined in Chapter 1, have been repeated here because they directed the study, and the methods explained in this chapter have been used to answer the various sub-questions.

What is the nature and extent of Grade 12 Life Sciences students' understanding of biological adaptation, before and after learning about natural selection?

a. What is the nature and extent of the scientific concepts about biological *adaptation* held by the students, before and after learning about *natural selection*?

b. What essential concepts are missing from students' explanations of biological *adaptation*, before and after learning about *natural selection*?

c. What is the nature and extent of the students' unscientific ideas about biological *adaptation*, before and after learning about *natural selection*?

d. To what extent do students exhibit alternative frameworks when explaining adaptation?

e. To what extent do the students use anthropomorphic and teleological language in their explanations of adaptation?

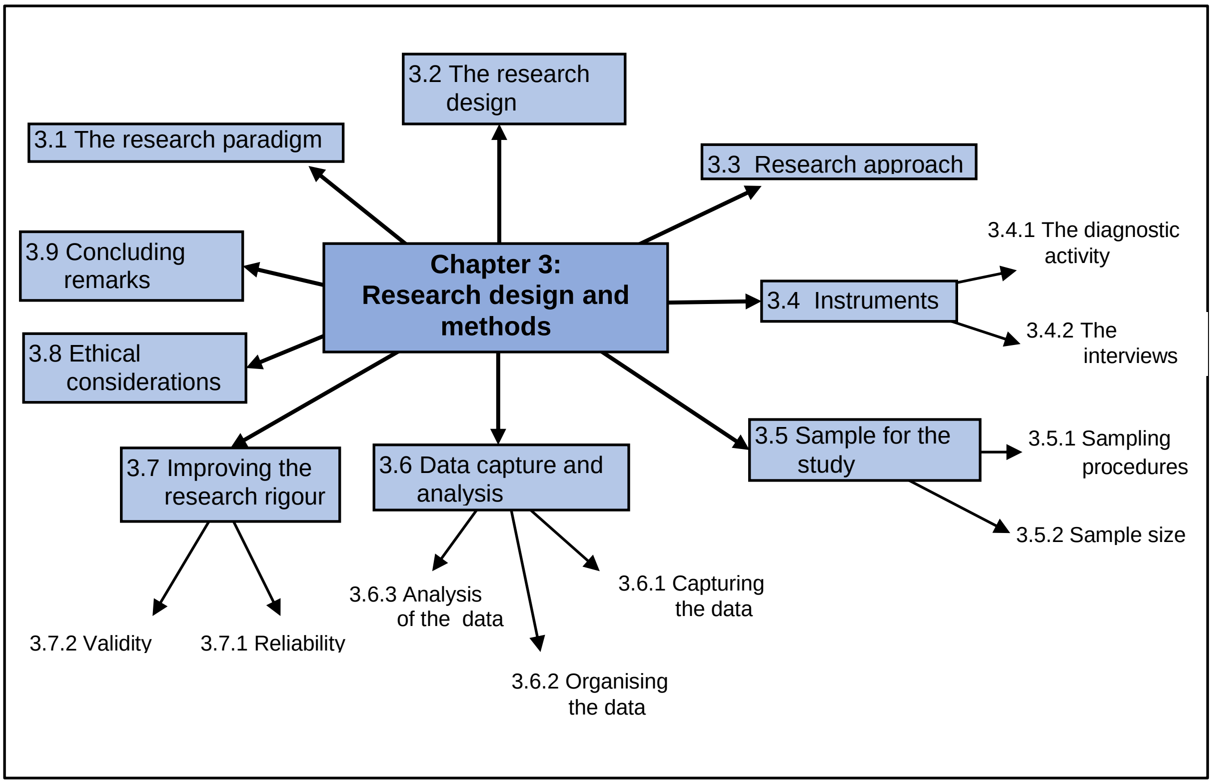


Figure 5: Structure of Chapter 3

3.1 THE RESEARCH PARADIGM

The human desire for knowledge and understanding motivates research (Cohen, Manion, & Morrison, 2005). In education, the knowledge and understanding attained through research is useful for informing policy and practice that could improve teaching and learning in schools in some way (Opie, 2004). Researchers, however, don't all agree on how to do research and, consequently, on the legitimacy of certain research findings. The clash between researchers has to do with their ontological beliefs about the world, which in turn affect their epistemological beliefs about the best way to investigate phenomena in the world. How researchers go about gathering information about the social world differs according to each researcher's worldview or paradigm. Paradigms are defined as "the worldviews or belief systems that guide researchers" (Tashakkori & Teddlie, 1998, p. 3). Three main paradigms have historically formed the basis from which social research in education is conducted: the positivist paradigm, the constructivist paradigm, and the pragmatic paradigm. Discussing these paradigms, along with pinpointing the specific paradigm from which this study has emanated, is important because of the varying beliefs about truth (ontology) and how it can be known (epistemology). Ontological beliefs about truth inform a researcher's epistemological understanding of how truth can be known and communicated to others, and influence their subsequent "thinking and actions" (Mertens, 2005, p. 7). In other words, a researcher's "ontological assumptions give rise to epistemological assumptions; and these, in turn give rise to methodological considerations; such as instrumentation and data collection" (Cohen et al., 2005, p. 3). The positivist and constructivist paradigms, explained below, represent two extreme positions, with much argumentation and disputation having occurred between researchers from both sides over such things as the nature of truth and reality (Tashakkori & Teddlie, 1998) and the validity of research methods (Onwuegbuzie, 2002). The second of these two matters of dispute is problematic for reasons discussed in a later paragraph.

Researchers fitting the positivist paradigm view truth as being real, external and objective (Poni, 2014). They regard the study of social phenomena in much the same way as the study of science phenomena, as external and independent of the researcher and, with the correct methodology (usually experiment and observation), objectively knowable (Cohen et al., 2005). According to this paradigm researchers need to remain "dispassionate" (Poni, 2014, p. 408) and "emotionally detached" (Johnson & Onwuegbuzie, 2004, p. 14) from their research participants to eliminate any bias and prevent any unintended influence upon the participants that may negate the objectivity of the study. The ontological emphasis on absolute truth and objectivity underpins their epistemological preoccupation with so-called 'quantitative' research methods. Hard facts and figures that are absolute and definitive are desirable, whereas the subjectivity associated with words like "sometimes"; "generally"; "typically"; etc., consistent with constructivist paradigm beliefs, are undesirable (Hammersley, 2014, p. 42).

Contrary to the objective stance on the nature of truth of the positivist paradigm, the constructivist paradigm takes a more post-modern view of truth, arguing that truth is subjective, and internally or socially constructed (Cohen et al., 2005; Mertens, 2005). Constructivists argue that "researchers should attempt to understand the complex world of lived experience from the point of view of those who live it" (Mertens, 2005, p. 12-13). The constructivist paradigm underlies so-called 'qualitative' research methods (Tashakkori & Teddlie, 1998) that are seen to be holistic because they allow "for the immersion of the researcher in the social settings, and facilitate intersubjective understanding between researcher and the participants" (Poni, 2014, p. 410). Constructivists argue that researchers are not external to the research participants, but a part of their experience. Researchers, therefore, should not stand at a distance to observe: they interact and get involved with the research participants to understand their thoughts and feelings. The difference between the positivist and constructivist paradigms, then, is whether a person views social reality as independent. external, given, and objectively real, or, rather, as socially constructed, subjectively experienced and the result of human thought as expressed through language (Opie, 2004).

Historically, traditionally qualitative methods (e.g. case studies) have been used to meet the ends of constructivists (e.g. theory generation) and traditionally quantitative methods (e.g. surveys) have been used to meet the ends of positivists (e.g. describing phenomena, and establishing causes). This historical divide between positivist and constructivist worldviews is problematic because it separates each paradigm according to a research approach (qualitative vs quantitative) rather than their ontological beliefs about research. To create a theoretical divide between qualitative and quantitative research methodology, when none exists, is counter-productive to the goal of research. Hammersley (2014, p. 39) argues that the "distinction between qualitative and quantitative is of limited use and, indeed, carries some danger". Such a position is consistent with the view that "a false dichotomy exists between quantitative and qualitative research approaches" (Onwuegbuzie, 2002, p. 521). Hammersley (2014, p. 52) argues that "The prevalence of the distinction between qualitative and quantitative method tends to obscure the complexity of the problems that face us and threatens to render our decisions less effective than they might otherwise be". Less effective decisions about methodology are likely to affect the quality of the research.

While the positivist and constructivist paradigms have dominated social research historically, many current researchers have adopted a position of paradigm relativity, or pragmatism. According to the Collins English Dictionary (1991, p. 1222) the word 'pragmatism' is defined as "action or policy dictated by consideration of the immediate practical consequences rather than by theory or dogma". Researchers within the 'pragmatic paradigm' are not so much concerned with the underlying philosophical understanding of the nature of truth as with using the most effective and practical research methods to answer the research problem (Burke, et al., 2004). Pragmatists emphasise, "the use of whatever philosophical and/or methodological approach works for the particular research problem under study" (Tashakkori & Teddlie, 1998, p. 5) because the use of multiple methods helps to achieve the research goals by "generating knowledge from diverse purposes" (Poni, 2014, p. 411).

The emphasis of pragmatists on using appropriate methods to achieve their research goals has several benefits. Firstly, a researcher can use a range of methods traditionally associated with one or other of the two historical paradigms to help answer their research questions. For example, certain relationships between variables may become apparent after conducting a survey using a questionnaire (traditionally thought to be 'quantitative' approaches), but the reasons why these relationships exist may only become apparent once interviews, which are traditionally considered to be qualitative, have been conducted (Fraenkel et al., 2012). Secondly, variables within a research project can be explored in more depth using mixed methods (Fraenkel et al., 2012). Thirdly, using multiple methods facilitates checking the validity of certain findings (Fraenkel et al., 2012) using the process of triangulation (Cohen et al., 2005). It is not all roses and sunshine for researchers who make use of multiple and mixed methodology, however. Some of the drawbacks include; the time, energy, and expense of conducting research using a range of methods. The reality is that to conduct mixed-methodology studies properly, a researcher needs to have the necessary skill and ability to carry out the investigations, which take time and energy to develop and conduct (Fraenkel et al., 2012).

While only the three commonest research paradigms (positivism, constructivism and pragmatism) are explained in the preceding paragraphs, many other different types of paradigms that can inform a research project exist in social research, for example feminism, realism, interpretivism etc. (Maxwell, 2005; Onwuegbuzie, 2002). Making the paradigm that underpins a research project clear is important since a clear philosophical and methodological stance helps the researcher explain and justify design decisions (Maxwell, 2005, p. 44). It also provides a base or structure upon which to build a research project instead of having to construct one from the beginning (Maxwell, 2005). As a researcher, I subscribe to the pragmatic paradigm. I have no philosophical allegiance to, or regard for, any of the so-called "purist" positions (Onwuegbuzie, 2002 p. 522) and am only familiar with the grounds upon which the 'paradigm wars' have been fought through reading, and not experience. My main concern is answering the research questions with the most appropriate and effective research methods that will provide relevant and accurate data, and that situates me in the pragmatic paradigm.

3.2 THE RESEARCH DESIGN

The word 'research' has many meanings in everyday English, but one very specific meaning in academia. Research refers to a series of steps, or a procedure, used to collect and analyse data to solve a problem (Creswell, 2012; Leedy, 1989). Research begins with a problem that generates research questions, and ends with some answers that illuminate the problem (Creswell, 2012). Between these two points lie many choices that the researcher needs to make (e.g. sampling, methodology) which will have an effect on the eventual outcome of the project. To ensure sound decision-making and the most efficient use of both time and resources, it is advisable that a research design be developed (LeCompte & Schensul, 1999; McMillan & Schumacher, 2010). A research design is like a "road map" that informs a driver how to proceed (LeCompte & Schensul, 1999, p. 61). The research design outlines the plan, at the outset of the project, that a researcher intends to follow to answer the research questions (McMillan & Schumacher, 2010). Good research designs will have details in them that save the researcher time and effort, while guiding the researcher toward reaching the desired outcome of the project (LeCompte & Schensul, 1999). The research design should include an outline of the problem, the formulation of research questions, an idea of who or what will make up the sample, information about the data gathering and analyses, and a conclusion (Leedy, 1989). The research design for this study is summarised in Figure 6, and explained in more detail in the rest of the chapter.

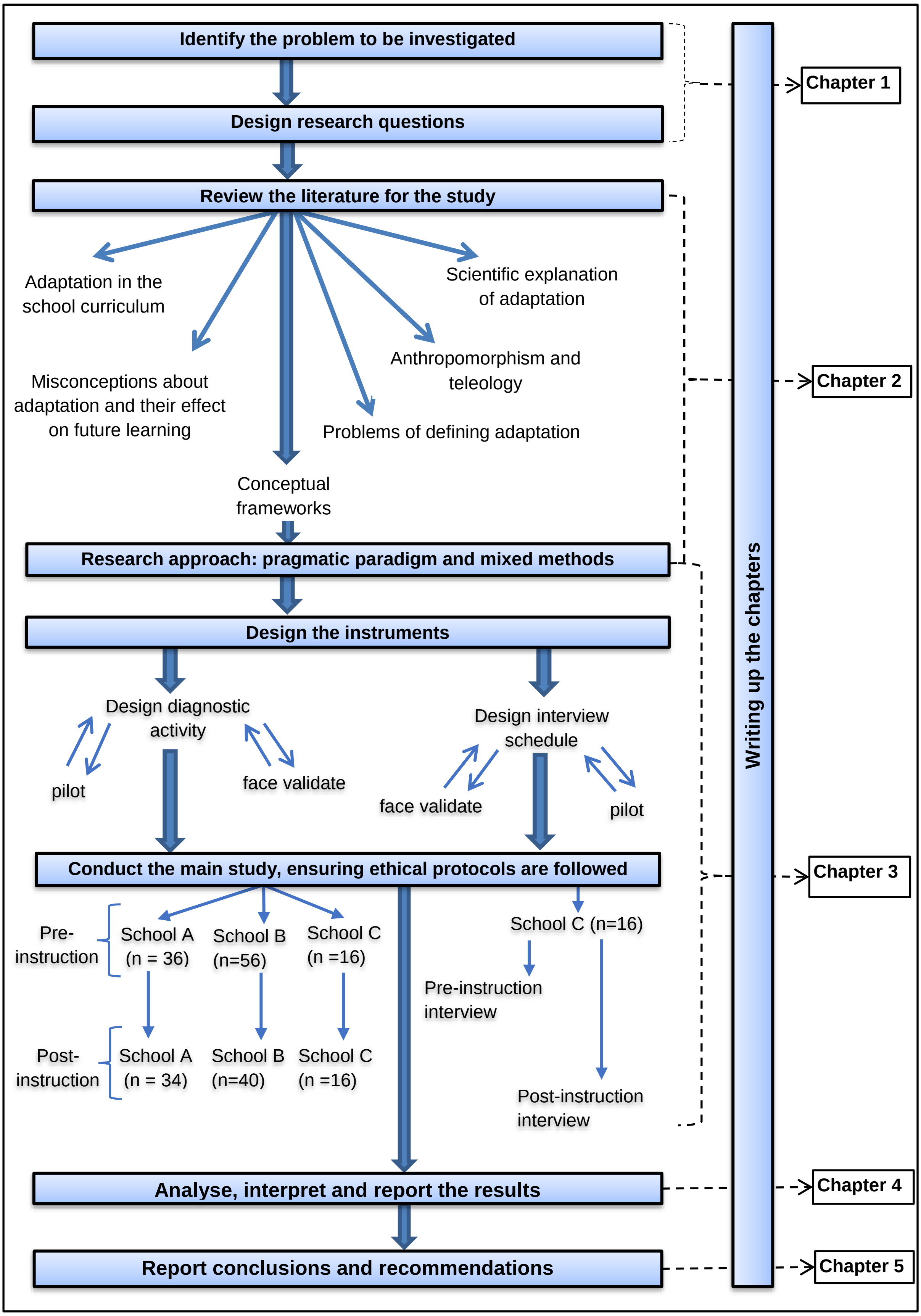


Figure 6: Outline of the research design

3.3 RESEARCH APPROACH

Two approaches (survey and case study) were used in this study to provide a deeper and richer understanding of a phenomenon than could be provided from the use of any single method (Creswell, 2012; Fraenkel et al., 2012). Surveys are used to gather data from a representative sample of a population (Cohen et al., 2005) to "describe the attitudes, opinions, behaviors (sic), or characteristics of the population" (Creswell, 2012, p. 376) at a particular point in time. Case studies involve an "in-depth exploration of a bounded system" (Creswell, 2012, p. 465). The word 'bounded' refers to the limits of the case in terms of time and place (Creswell, 2012), like a child, a class, a school or a community. Mixing approaches is appropriate when one method or approach is not sufficient to answer the research questions. Creswell (2012, p. 536) argues that the strengths of one method can be used to offset the weaknesses of another. In this study, case studies were used to augment survey information. This provided more detailed insight into student thinking, with the aim of probing students' ideas about adaptation and any unscientific ideas they might have.

3.4 INSTRUMENTS

Two instruments were used in this study; a diagnostic activity for the survey and semi-structured interviews for the case study.

3.4.1 The diagnostic activity

While the most frequently used form of data collection in the survey approach is the questionnaire, a diagnostic activity is also a useful data collection tool. The term 'diagnosis' in the non-medical sense, according to the Collins English Dictionary (1991, p. 434), is a "thorough analysis of facts or problems in order to gain understanding and aid future planning". In education a diagnostic activity is, among other things, a means of assessing what students know about a particular topic at a specific point in time by engaging students in an activity, often written. In the normal process of teaching this information can then be used to guide further action or develop a teaching plan (Drecker & Fraser, 1991). In this way, the primary outcome of a diagnostic activity is not a score or a mark, though one may be given, but rather to identify areas of weakness or strength, or, in my study, students' scientific and unscientific ideas, some of which might require remedial action (Drecker & Fraser, 1991; Romine, Schaffer, & Barrow, 2015). As Modell, Michael, and Wenderoth (2005, pp. 23–25) note:

> "…uncovering a misconception, if used in a diagnostic process, helps the instructor gain insight into how the student is thinking about a concept or set of concepts" […] "and can help the instructor identify the level of complexity at which the difficulty is occurring".

While diagnostic activities are often used in conjunction with remedial action (Drecker & Fraser, 1991; Modell et al., 2005), no deliberate intervention was undertaken in this study. Teachers were specifically instructed not to teach natural selection any differently from how they had taught the topic in the past.

The aim of the diagnostic activity in this study was to establish how scientific the students' understanding of adaptation was before and after learning about natural selection and to assess the nature and frequency of unscientific ideas students held about the topic of adaptation, especially those to do with the 'evolution on demand' alternative framework, usually expressed with teleological and anthropomorphic language. The use of the diagnostic activity was important for answering all five of my research questions.

Designing the diagnostic activity

Table 11 shows the general structure of the diagnostic activity. Open-ended questions were used for the explanations and scenarios because they allow respondents to write their own responses (Cohen et al., 2005). This is useful when a researcher wants detailed information about the ideas, opinions or beliefs about a given topic (Fraenkel et al., 2012; McMillan & Schumacher, 2010). Open-ended questions do have their drawbacks, however. Firstly, open-ended questions take longer to answer because students are writing full sentences as opposed to ticking multiple-choice boxes or writing out single words, as is the case with closed-ended questions. Secondly, second-language speakers may have trouble understanding questions and often battle to communicate their ideas for open-ended questions (Probyn, 2005). Thirdly, open-ended questions are generally difficult to code because answers vary from student to student, making it challenging to develop a standardised coding scheme. Finally, open-ended questions require a lot more time to analyse because there is a lot more writing, and they open the door to subjectivity in interpretation which may have an impact on the validity of the claims made by the researcher (Cohen et al., 2005). Two open-ended questions were used in the first two questions of Part 1 of the diagnostic activity and the last two questions of Part 2 of the diagnostic activity.

Table 11: The structure for the pre-instruction activity

Part	Content	Justification
Part 1	Scenario 1 involved a colour change evolving subsequent to an environmental change.	Open-ended questions were deemed best to establish students' ideas in their own words, and to prevent students being prompted by multiple-choice options
	Scenario 2 involved the evolution of an advantageous structure in elephants over time	
	One multiple-choice question to establish whether students held teleological ideas about organisms living in desert conditions.	Multiple-choice format was used based on Jungwirth (1975). The wording of the options was modified slightly so that the difference between each option stood out more.
Part 2	Closed-ended questions requesting demographic information from the students.	• To establish the backgrounds of the students who had attended different primary schools, and identify in which grade they covered the topics. The curriculum at the time did not specify the grade in which the content should be taught. • These questions were not repeated in the post-instructional test.
	Two open-ended questions requesting students to explain the terms 'adaptation' and 'natural selection'	

Closed-ended questions have a prescribed list or range of responses from which the respondent may choose (e.g. multiple-choice or a rating scale) and are commonly used with large samples (Cohen et al., 2005). Closed-ended questions are popular because they are quick to complete, uncomplicated to code, do not require a high degree of literacy on the part of the respondents and the researcher can define the parameters of the study without the respondents liberally writing as much or as little as they please (Cohen et al., 2005; Creswell, 2012; Fraenkel et al., 2012). Closed-ended questions can, however, prompt respondents towards certain answers based on the options provided, and they limit the amount of extra information a respondent can provide (Fraenkel et al., 2012). Closed-ended questions were used in the last question of Part 1, and the first few demographic questions of Part 2.

Part 1 of the diagnostic activity

The 'scenario" questions focused specifically on eliciting students' explanations of the process of adaptation, but used two different contexts for the adaptations described. There were three reasons for this: firstly, it provided an opportunity to determine the extent to which the context of the question influenced student reasoning. The idea of using scenarios was taken from Engel Clough and Wood-Robinson (1985a) who asked students open-ended questions on a caterpillar and an artic fox and found that the context of the question influenced students' answers. Secondly, it allowed me to determine to what extent those unscientific ideas might be linked to the 'evolution on demand' alternative framework and were consistent between a student's responses to the two scenario-based questions. This was to help provide the multiple sources of evidence needed to establish whether particular misconceptions occurred consistently, a need suggested by Fisher and Lipson (1986). Thirdly, it introduced a new level of complexity as defined by Bloom's taxonomy of cognitive levels. It required students to do more than recall "specific facts" (Falk, 1971, p. 33), as considered in a knowledge-level skill (level 1 in Bloom's taxonomy). The questions required students to rethink, reorder and translate what they already knew before they answered (which requires level 2 skills – comprehension) and then apply their knowledge to new and unfamiliar situations, which involves level 3 cognitive skills – application (Amer, 2006; Falk, 1971).

Because this research involved a pre- and post-instruction investigation, two equivalent versions of the diagnostic activity were developed to test students' understanding of adaptation before and after instruction on the topic of natural selection (see Table 12). Using identical questions before and after instruction could be problematic in terms of familiarity of questions for the post-instruction instrument, affecting the validity of the results. I therefore took great pains to develop an instrument with equivalent forms of the same questions on the post-instruction activity. I hoped this would reduce the 'practice effect' (Gardner, Schafe, Thein, & Watterson, 1975), where students have had practice answering that item and also the opportunity to discuss the answer with their peers.

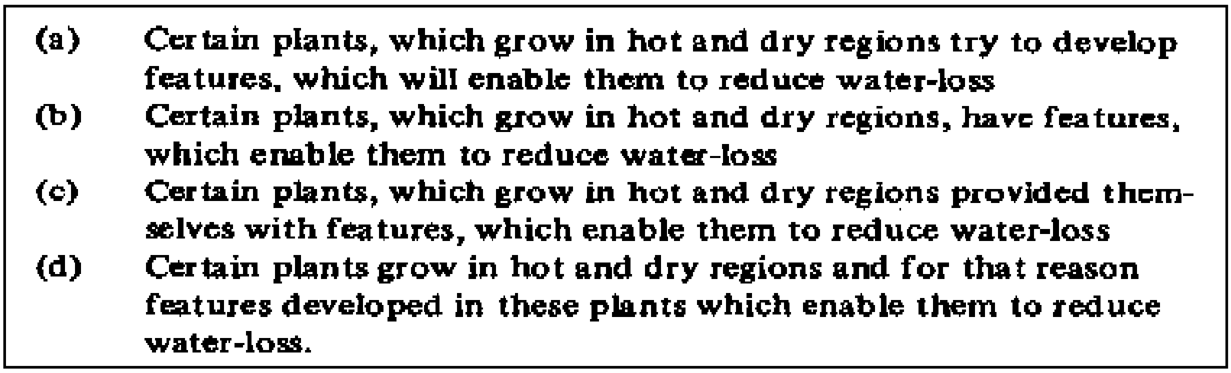
A number of factors were taken into account to ensure that the questions on the pre- and post-instruction diagnostic activities were different but equivalent. The first scenario question of the pre- and post-instruction activities made use of an insect (peppered moth and the fruit chafer beetle); both specified dates (1800's and 1980's); and each included an obvious environmental factor (soot/ drought), and phenotypic differences becoming apparent (colour change in the population). The second scenario-based question made use of mammals (elephant and a seal); involved a change in a structural component to improve a physiological function (ears/ lungs); and both prompted students to begin their explanation by referring back to earlier adaptive states of the organisms. It is also important to note that the second question specifically asked students to "explain, step-by-step…" which is different to the phrasing of the first question. This wording came about after the first pilot study, where students were not answering the "how" question asked, which was expected to elicit an answer explaining the mechanism of natural selection. The instruction "step-by-step" was added to provide direction to students' answers. The third question was made equivalent by keeping a similar hot desert environment and similar multiple-choice options, although the organism was changed from a plant to a camel.

Table 12: Pre- and post-diagnostic activity questions, showing equivalence

#	Pre-instruction questions	Post-instruction equivalents
1	The peppered moths that lived in England in the 1800's were generally grey in colour and were well camouflaged on the grey tree trunks. During this period, the industrial activity in England increased the amount of smoke and soot, causing tree bark to become darker in colour. More dark moths then started to appear. Explain, as fully as possible, how you think this happened. (Shtulman, 2006, p. 187)	The fruit chafer beetles in South African gardens in the 1980's were generally yellow in colour and were well camouflaged on yellow flowering plants. A drought during this period reduced the number of yellow flowering plants. The fruit chafer beetle found an alternate food source on leafy acacia trees. More emerald (green) chafer beetles started to appear. Explain, as fully as possible, how you think this happened. (self-constructed item)
2	The large ears of an elephant play an important role in the regulation of an elephant's body temperature. Explain, step-by-step, how elephants developed large ears. You should start your explanation by referring to elephants that had smaller ears in the distant past. (self-constructed item)	The first seals could only stay under water for short periods before they had to come up to breath. However, today most seals can remain under water for a long time without breathing (nearly 45 minutes). This a big advantage when they hunt for fish deep under the sea. Explain, step-by-step, **HOW** modern seals developed the ability to hold their breath for a long time under water (i.e. explain how the change happened). You should start your explanation by referring to ancient seals that could stay under water for only a couple of minutes. (Lawrence, work in progress)
3	From the options below, circle the answer that is the ***most scientifically correct explanation*** for how desert plants have become suited to the environment in which they live. a) Plants which grow in hot and dry regions need to survive so try to develop features which enable them to reduce water loss. b) Plants which grow in hot and dry regions have features which enable them to reduce water loss. c) Plants which grow in hot and dry regions develop features which enable them to reduce water loss. d) Plants in hot and dry regions develop features in order to reduce water loss. Please explain why you selected that answer. (Jungwirth, 1975)	From the options below, circle the answer that is the *most scientifically correct explanation* for how camels have become suited to the environment in which they live. a) Camels in the hot, dry desert need to survive so try to develop features which enable them survive the hot environment. b) Camels in the hot, dry desert have features which enable them to survive the hot environment. c) Camels in the hot, dry desert develop features which enable them to survive the hot environment. d) Camels in the hot, dry desert develop features in order to survive the hot environment. Please explain why you selected that answer. (self-constructed item)

Ideas for the questions were taken from a number of sources. The example of the peppered moth is frequently used in the literature to assess understanding of either adaptation or natural selection (e.g. Anderson, Fisher, & Norman, 2002; McComas, 1994; Moore et al., 2002). The question was based on one from Shtulman (2006, p. 187) but the wording was edited so that adaptation and not variation became the main thrust of the question. Some context was also provided to the students, as I assumed that students in the sample were unfamiliar with the example of the peppered moth. The fruit chafer beetle was a self-constructed and hypothetical example designed as an equivalent question to that of the peppered moth in ways mentioned in the previous paragraph. The example of the elephant for the second question on the pre-instruction activity was self-constructed. The idea for the elephant came about when thinking about an animal that South African students would be familiar with. The example of the seal for the second question of the post-instruction activity was used with permission from Lawrence (work in progress). The wording of the question was altered to be equivalent to the wording of the elephant question on the pre-instruction activity.

The final question for Part 1 was a multiple-choice question where students had to select the most scientific answer from four possibilities (see Table 12). Three of the options were regarded as ‘unscientific’ as they contained teleological language (options a, c, d), with option (a) also using anthropomorphic language, while one of the options had no teleology and was regarded as being more scientific (option b). Students were then asked to explain, in their own words, why they chose the particular option they did, to see if they could correctly identify the problems with the wording of statements that they did not select or to see if they had the correct or faulty reasoning for the option they did select. Both the pre-instruction and post-instruction questions were based on one from Jungwirth (1975, p. 97) (see Figure 7 for the original question).



(a) Certain plants, which grow in hot and dry regions try to develop features, which will enable them to reduce water-loss
(b) Certain plants, which grow in hot and dry regions, have features, which enable them to reduce water-loss
(c) Certain plants, which grow in hot and dry regions provided themselves with features, which enable them to reduce water-loss
(d) Certain plants grow in hot and dry regions and for that reason features developed in these plants which enable them to reduce water-loss.

Figure 7: Original multiple-choice question (Jungwirth, 1975)

The pre-instruction question kept the same example as Jungwirth (1975) while the post-instruction question used the example of a camel. The wording of the multiple-choice options was changed for a number of reasons. Firstly, to make the distinction between each option more apparent. Secondly, emphasis, in the form of underlining, was added to each choice to highlight the difference between the wording of each choice and to point students to the main part of each choice that they needed to focus on (see Figure 7 for the original question).

The equivalent form of the question made use of the same environmental conditions (i.e. a desert) but changed the organism from a desert plant to a camel (see Table 12). It should be noted, however, that Heredia, Furtak, & Morrison (2016) note that students are more likely to choose the scientifically correct options on multiple-choice questions involving animal examples than plant examples. In hindsight, this is a problem that could have affected the equivalence of the third question as the pre-instruction activity used a plant as an example and post-instruction activity used an animal.

Part 2 of the diagnostic activity

Part 2 started with a number of closed-ended questions about the student’s educational history, such as which primary school they had been to and in which grade they had learned about adaptation and natural selection, etc. Asking these questions allowed me to better understand the demographics of the sample. These demographic questions were not repeated for the post-diagnostic activity.

Part 2 of the diagnostic activity included two open-ended questions. These asked students to explain their understanding of *adaptation* and *natural selection* respectively. The question did not ask them to 'define' adaptation or natural selection, but instead asked students to 'explain' their understanding of these two concepts in order to assess student understanding of these two evolutionary topics as expressed in their own words. According to Bloom's taxonomy (Amer, 2006) questions asking for definitions would probably involve cognitive level 1 ('knowledge' questions) as students' could simply use pre-learned information. By requiring them to 'explain' students would be more likely to use their own wording, thus making it a level 2 (comprehension) question.

Face validating the diagnostic activities

Both versions of the diagnostic activity went through an iterative process of face validation. Face validation involves an expert or panel of experts reviewing the instrument to see whether it appears to measure what it is intended to measure. The researcher should ask the experts to consider a range of factors that could affect the results, thus leading to inappropriate claims from the data. Firstly, the clarity of the instructions is checked. Instructions shouldn't be ambiguous or complicated, so respondents are less likely to misunderstand the instructions and make errors. Ideally, instructions should be clear, concise and written with language that is familiar to the respondents (Cohen et al., 2005). Secondly, the wording of the questions is important to the success of the activity. Like the instructions, the wording needs to be clear, unambiguous, and asked in such a way that the students answering the question will know exactly what is being asked and answer as truthfully as they possibly can (Davidson, 1970, cited by Cohen et al., 2005). An expert in research methodology helped with the layout of the activity to improve user-friendliness, and pointed out problems with the wording of both the instructions and the questions so that the instrument was at an appropriate level for Grade 12 English second-language students to answer. The instrument was then modified and looked at a second time. Final changes were discussed together before the instrument was piloted.

Pilot testing the pre-instructional diagnostic activity

A pilot test is a simulation of the main study, conducted with a small sample before the main study is conducted. This allows the researcher to check if there are any problems that would affect the validity of the instrument and the procedure of its administration (van Teijlingen & Hundley, 2001). Ideally the participants of the pilot test should have similar characteristics to those in the actual study and the instrument should be administered in the same fashion as that intended for the main study (McMillan & Schumacher, 2010; van Teijlingen & Hundley, 2001). Researchers are looking for at least three types of feedback from a pilot study that will inform further refinement of the activity or its administration before the main study is conducted (Creswell, 2012; McMillan & Schumacher, 2010; Opie, 2004):

1) Information from the administration process. The length of time the instrument takes to complete.
2) Information received from the students themselves, for example, the clarity of the instructions and questions.
3) Information deduced by analysing the students' answers. The researcher may notice conflicting or confusing responses from the students which may indicate that the questions on the instrument were not understood by the students (Creswell, 2012).

In this study, the pre-instruction diagnostic activity went through two pilot studies before being used for the main study. The instrument was first piloted the year before the main study with 10 Grade 12 students from the school where I was teaching at the time. Before they started, students were asked to note down the time they started the activity, and, at the end of the activity, the time they finished. The goal was to limit the average time it took students to complete the activity to under 25 minutes so as not to use up too much of the Grade 12 students' precious class time. Each student was asked to provide written feedback on any problems they had with the clarity of the instructions and questions, in a block such as the one in Figure 8. A copy of the pre-instruction diagnostic activity is provided in Appendix A).

Did you have any problems understanding the instructions Yes ☐ No ☐
about what you had to do to answer these questions?

If "yes" please explain your difficulty:

Figure 8: Feedback block inserted after each part of the pilot diagnostic test

After the first pilot test, a number of changes were made. The example of the second scenario-based question was amended from a woodpecker to an elephant. It was changed because the woodpecker example was less familiar to students than its replacement (an elephant), and the context of the question was more complex so the students had to engage mentally with the problem. Secondly, a fourth, multiple-choice question was included in the first pilot test. This multiple-choice question used a different example but essentially was a repeat of the first multiple-choice question and was discarded for the second pilot test. When I analysed answers received in the first pilot test, the wording of the remaining multiple-choice question appeared to be ambiguous. The question was improved by rephrasing each choice to improve the clarity of the choice and by underlining the important phrase in each choice. As a result of changes having been made after the first pilot test it was decided to pilot the test for a second time, with 10 other Grade 12 students from the school where I was teaching at the time. After looking at the students' feedback on the questionnaire and reviewing, with my supervisor, the sorts of answers given to the questions in the second pilot of the pre-instruction diagnostic activity the instrument was considered to be ready for use in the main study.

Some limitations to pilot studies may exist. The success of a pilot test does not guarantee that the main study will be successful. Problems may only emerge during the main study that did not emerge during the pilot test (van Teijlingen & Hundley, 2001). A decision about whether to include the pilot data in the main study is important. There is a chance of "contamination" which occurs when significant changes are made to the instrument after the pilot study and before it is used in the main study, which could render the pilot data "…flawed or inaccurate" (van Teijlingen & Hundley, 2001, p. 3), so an argument can be made for the exclusion of the pilot data. The results obtained in the pilot study were not included in the main study because the pilot studies were done a year before the main study, and by the time the second pilot test was written these students had already learned about natural selection. This meant they could not be a part of a pre-instruction and post-instruction sample.

The post-instruction diagnostic activity was not piloted. The overall structure of the post-instruction activity remained unchanged from the pre-instruction instrument, only the examples in each of the questions changed. Face validation of the new 'equivalent' questions was considered sufficient to maintain the rigour of the post-instruction instrument. Copies of the two versions of the diagnostic activity (pre- and post-instruction) can be found in Appendix A and Appendix B respectively.

Administering the diagnostic activities

There were two important elements to the administration of the activity; i.e. *how* and *when* they should be completed. Because three different schools were involved in this project, and the teachers at the schools administered the instruments, the administration of the diagnostic activity needed to be standardized to minimise reliability and validity problems, as advised by Creswell (2012). A list of instructions was given to each teacher (see Appendix C). The activity was administered under test conditions so that students couldn't influence each other's answers. On the issue of *when* the instrument needed to be administered, the activity was handed out at all three schools after the Grade 12 section on genetics had been taught and before the start of the section on evolution. The post-instruction activity was administered after the section on evolution had been completed.

As mentioned earlier, Part 1 had two scenario-based questions and a multiple-choice question. Part 2 consisted of general information about the student, three yes/ no questions about their exposure to the topic of adaptation in previous grades, and it asked students to define adaptation and natural selection. Logically, the general information about a student (Part 2) should come before the scenario-based questions (Part 1). However, because Part 2 contained words (e.g. adaptation/ natural selection) that might prompt students to think in a specific direction or give the students a clue of what the scenario-based questions were about, I asked that the scenario-based questions be completed and collected in before what became Part 2 was handed out, for both the pre- and post-instruction activities.

3.4.2 The interviews

Written responses to research questions have limitations because they do not always provide detail and insight into students' thinking. Opie (2004) notes that many students either do not want to, or are not confident enough to, explain their feelings, thoughts, or beliefs on paper – especially if they are English second-language speakers. Interviews involve face-to-face verbal encounters between researcher and participant, to elicit the required research data. Fraenkel et al. (2012, p. 451) explain, "the purpose of interviewing people is to find out what is on their minds – what they think or how they feel". Interviews provide an environment in which respondents are encouraged to think and verbally express their ideas, thoughts, attitudes, expectations and feelings about the topic under discussion. Interviewers can ask for more detail, or rephrase questions to help the interviewee understand and/or answer the question (Fraenkel et al., 2012; McMillan & Schumacher, 2010). Interviews allow for participant responses to be "probed, followed up, clarified, and elaborated on to achieve specific and accurate responses" (McMillan & Schumacher, 2010, p. 205). Probes are additional questions or sub-questions that are added by the interviewer, in keeping with the theme of the main question, to help elicit additional responses from interviewees (Creswell, 2012). The opportunity the interview situation provides to probe students' answers, is the primary reason why interviews were used in this study.

Interviews can have weaknesses, which researchers need to be aware of so they can try to reduce them. Some of the weaknesses relate directly to interview technique. Firstly, the presence of the researcher may influence how the interviewee answers the questions (Creswell, 2012; McMillan & Schumacher, 2010; Opie, 2004). Secondly, interviewers may inadvertently ask leading questions that cause students to answer in ways that do not reflect their actual ideas, sometimes unintentionally reflecting the researcher's point of view (McMillan & Schumacher, 2010). Thirdly, interviews are open to bias and subjectivity (McMillan & Schumacher, 2010) in that the views of the interviewee may be filtered, summarized or paraphrased by the interviewer in a way that does not convey the intended meaning of the interviewee (Creswell, 2012).

A number of different types of interviews have been described in the literature (Fraenkel et al., 2012; McMillan & Schumacher, 2010; Opie, 2004). The structure of the interview is likely to depend on the purpose of the interview. *Structured* interviews, are essentially oral questionnaires which require short, often one-word, answers to closed questions (Fraenkel et al., 2012; McMillan & Schumacher, 2010). This sort of interview structure is formal, rigid, and does not allow for any digression from the interview schedule, so does not provide room to probe interviewee responses (McMillan & Schumacher, 2010; Opie, 2004). The rigidity of structured interviews was unsuitable for the purposes of my research, so this format was not used. *Unstructured* interviews are generally informal and tend to mimic a casual conversation that follows the interests of both the researcher and the interviewee (Fraenkel et al., 2012). Unstructured interviews do not have a set type or sequence of questions and tend to gather a lot of information that takes a long time to analyse (Fraenkel et al., 2012; Opie, 2004). The unstructured format and the lack of a guiding interview schedule for the interview is why I chose not to use unstructured interviews. It is not advisable for novice researchers, such as I am, to conduct unstructured interviews (Opie, 2004). *Semi-structured* interviews have a high degree of structure in the sense that an interview schedule is pre-planned for the interview, with a list of the questions and probes the researcher plans to ask (Opie, 2004). However, a researcher can digress from the planned schedule or probe responses spontaneously during the interview (Opie, 2004). I used semi-structured interviews because the interview schedule is a helpful tool for an inexperienced researcher to refer back to, while at the same time allowing for digression to probe and ask for clarification (McMillan & Schumacher, 2010).

Preparatory steps taken before the interviews

Preparing for an interview normally involves selecting the sample, developing an interview schedule (Fraenkel et al., 2012; McMillan & Schumacher, 2010), brushing up on interview technique and etiquette (McMillan & Schumacher, 2010), planning the dates and times for each of the interviews and communicating these to the interviewees (Leedy, 1989), and piloting the interview (Opie, 2004).

The sample for the interviews was related to the purpose of the interviews. The purpose of the interviews in my study was to clarify what the students meant in their responses to the pre- and post-diagnostic activities, and to follow up on interesting answers. It is not always clear what students mean in their written responses. For example, students use pronouns like 'they' and 'their' in reference to the subject of the question and it is unclear if they are referring to one individual or an entire population. Such problems in interpreting the students' wording limits the accuracy of the coding and the results of the study. Interviews can help to clarify what the student meant in the written response. Ideally, each student in the sample should be interviewed about their responses. Because of the sample size in my study, this was not feasible. The student cohort at the school where I teach was relatively small (n = 16), and the students were readily accessible, so I interviewed the whole group from just my school.

This had the added advantages of including students with a range of abilities and not having to select students with specific answers, as all were interviewed.

Because the main purpose of the interviews was to better understand what each student meant in their written responses, the questions were based on the students’ answers to the open-ended scenario questions from diagnostic activities. Interview schedules were specifically tailored for each student and contained carefully prepared questions that the interviewer planned to ask the student during the interview, as advised by McMillan & Schumacher (2010). The questions were sequenced in the order that the interviewer planned to ask them, as advised by Leedy (1989). Table 13 provides an extract from one interview schedule, to show the format of the schedule, and the types of probes that were pre-prepared. All questions are written in italics. Text that is not italicised indicates reminders to me as the interviewer of what I needed to consider during the interview. The main question to ask the student appears in the left-hand column underneath the student’s response. These questions were important and needed to be asked during the interview. The questions in the right-hand column were follow-up questions that were used to clarify a question for the student, to probe the student for more insight into their original answer or to remind the interviewer what to ask.

Table 13: Extract from the interview schedule, showing the format of the schedule

<table>
<tr><td colspan="2">**Student’s answer in the diagnostic activity (needed to be probed):**
Well the bark on the trees either was absorbing the smoke or was getting covered in soot therefore changing the colour of the tree that these moths land on. This would cause the moths to **adapt** as grey would not be a suitable camouflage. So I believe this is adaptation of the colour of the moths. They adapted to suit the new environment in this period.</td></tr>
<tr><th>Main questions</th><th>Follow-up questions or probes</th></tr>
<tr><td>Highlight the word “adapt”
1. *Please explain what you mean when you use the word ‘adapt’ in your answer.*</td><td>• *What made you use the word ‘adapt’ in this instance?*
• *How do the moths adapt?*
• *Do they decide to change? What drives the change that the moths experience?*</td></tr>
<tr><td>Highlight “cause the moths to adapt”:
1. *Please explain what you mean when you say that “this would cause moths to adapt?”*
2. *Why would they change from the grey colour to another colour?*</td><td>• *How would the change in bark colour cause the moths to adapt?*
• *Why not pink or green?*</td></tr>
</table>

The next step was to decide on a method to obtain a record of the interview. Two main methods are common. The first option is for the researcher to take notes. Note-taking might be less intimidating for the interviewee, but it is both time consuming and distracting for both the interviewee and the interviewer, who is trying to record as much data as possible (Cohen et al., 2005). It also means that a researcher will need to rely on memory for any information not recorded in the notes, which reduces reliability (Cohen et al., 2005; Creswell, 2012; McMillan & Schumacher, 2010). The second option is audio-recording. Audio-recording may be more intimidating for interviewees and, ethically, permission must be gained from the interviewee before they commit themselves to being interviewed. Audio-recordings do need to be transcribed, which is also a time consuming process (Creswell, 2012; McMillan & Schumacher, 2010). However, audio-recording an interview means that a word-for-word record of the interview exists that a researcher can refer back to at any time. It also frees up the interviewer during the interview to concentrate on what the interviewee is saying rather than on the task of writing notes (Fraenkel et al., 2012). Of the two options for recording the interviews, I chose to use audio-recording for the reasons mentioned. The recordings were transcribed and a copy of both the audio-tape and the transcription kept on a password protected computer. Permission had already been granted by all the students and their parents to allow me to use the voice-recorder in the interview. This is discussed in Section 3.8 (starting on p. 65), on ethics.

The final preparatory step was to plan the date and time of the interviews (as recommended by Leedy, 1989). I asked each student to choose a date and time that best suited them from a list of scheduled times when I was available, during their break times and after school. The break times were deemed suitable as each interview was intended to be no more than 15 minutes long and first break at the school is half an hour. The interviews were set two weeks in advance and I reminded each student of their planned interview the day before the scheduled interview, as advised by Opie (2004).

Piloting the interview

Before the interviews were piloted, several interview schedules were face validated by an experienced researcher, knowledgeable about research techniques and about evolution, who checked that the questions were appropriate (that they were suitable for the student based on their written answers), understandable, and logically sequenced. Following this, two interview schedules were piloted before the interviews for the main study began. Piloting interviews helps the interviewer check procedure (McMillan & Schumacher, 2010), to remove or change any confusing questions which interviewees do not seem to understand (Opie, 2004), to check the likely length of the interview so interviewees can be told how much time will be needed (McMillan & Schumacher, 2010; Opie, 2004), and to check that the planned introduction makes the interviewee feel comfortable and at ease during the interview (McMillan & Schumacher, 2010). It became apparent during the pilot studies that the length of each interview would vary significantly (between 10 and 20 minutes) and that a highlighter was needed to direct students' attention to the phrase of interest in their diagnostic activity response to focus their attention on that phrase being probed and so that they did not lose their point of reference. As discussed in a previous section, there is some debate about whether data collected during pilot studies should be included in the main research group. While some authors note that students involved in a pilot study should not be included in the main research group (McMillan & Schumacher, 2010; Opie, 2004; van Teijlingen & Hundley, 2001), I included students from the interview pilot study in the main sample for the interviews because the two pilot studies revealed no problems with either the wording of the questions, or the administrative procedure. My supervisor confirmed this after listening to the audiotapes and reading the transcripts from the two pilot interviews.

Conducting the interviews for the main study

Generally, two interviews were conducted per day in a quiet classroom away from the break-time and after-school noise, as advised by Opie (2004). Each student was greeted at the door and shown to their seat. Before beginning the interview I again asked each student for permission to audio-tape the interview. The first question of the pre-instruction questionnaire was designed as an ice-breaker to get the students talking and help them feel comfortable. As a new teacher at the school, and having taught the Grade 12's for less than a month, I felt it necessary to stimulate conversation prior to the pre-instruction interviews with an ice-breaker question (as advised by McMillan & Schumacher, 2010). This question was not repeated in the post-instruction interview as I had taught the students for five months by that time and the students knew me and were comfortable talking to me and I to them. As stated previously, students were asked questions about their answers to the scenario-based questions in both the pre- and post-instruction diagnostic activities. Before I asked the students about their written responses to the questions, students were asked to read the relevant written answer to be probed in the interview, to remind them what it was that they had said before, thus setting the scene for the interview questions. The duration of the interviews varied depending on the number of questions asked in the interview and the time it took for students to answer them (see Table 14).

Table 14: Lengths of pre- and post-instruction interviews, in minutes and seconds

	Longest interview	Shortest interview	Average length
Pre-instruction interviews	17:15	07:26	11:12
Post-instruction interviews	16:45	04:30	11:42

3.5 SAMPLES FOR THE STUDY

A sample is a portion (sizes vary) of a larger population. In research, ‘populations’ refer to everyone with a specific set of characteristics that are of interest to a researcher (Creswell, 2012). Because it isn’t always feasible to collect data from the entire population, a sample that is representative (ideally) of the population is selected (Fraenkel et al., 2012). The process of selecting a sample is known as sampling (Creswell, 2012).

3.5.1 Sampling procedures

Probability sampling is the best form of sampling because it provides a sample that is more representative of the entire population. Probability sampling is important where the researcher is looking to generalise the research findings to the whole population (Creswell, 2012; Gall, Borg, & Gall, 1996; McMillan & Schumacher, 2010). Random sampling, where each member of the population has an equal chance of being selected, is the ideal method of probability sampling (Creswell, 2012; Gall et al., 1996; McMillan & Schumacher, 2010). This is not always feasible, however, as a population can be too large to contact everyone, or may be spread over a large geographic area (Creswell, 2012; McMillan & Schumacher, 2010).

I used non-probability sampling in the form of convenience sampling in this study. Convenience sampling involves selecting research participants because they are “available, convenient and represent some characteristic the investigator seeks to study” (Creswell, 2012, p. 145). This form of sampling is frequently used in educational research because of time, geographic, and economic constraints (McMillan & Schumacher, 2010). Three private schools in Johannesburg were selected for my study because they were accessible to me. I was teaching at one of the schools and had colleagues at the other two schools who were willing to consider facilitating my research at their school. Because this form of sampling is non-random, attempts to generalise the research findings to a population should be done with caution (McMillan & Schumacher, 2010). The researcher cannot generalise to the whole population with confidence because the sample may not be representative of the whole population (Creswell, 2012), as the selected sample may be biased in some way (Fraenkel et al., 2012). It may also not be the researcher's intention to generalise the research findings to the entire population but to rather describe problems or challenges within a particular specific context. McMillan and Schumacher (2010) note that generalising findings from convenience samples should be limited to students similar to that of the research sample.

3.5.2 Sample size

Sample size is an important consideration for researchers because larger samples permit generalisations to be made with more confidence (McMillan & Schumacher, 2010). It is therefore advisable that researchers select as large a sample as possible or feasible from the population, if they wish to generalise the results from their study (Creswell, 2012; Gall et al., 1996; McMillan & Schumacher, 2010). Fraenkel et al. (2012, p. 102) point out that a "sample should be as large as the researcher can obtain with reasonable expenditure of time and energy". Gall et al. (1996) suggest that a sample of 100 students is the minimum for survey research and Fraenkel et al. (2012) note that qualitative studies will usually have a sample of between 1 and 20 students. All of the Grade 12 Life Science students from the three schools involved in the research, and who gave consent and who were present for both pre- and post-diagnostic tests, made up the sample for the survey (n = 90). Grade 12 Life Sciences students from one school formed the sample for the interviews (n = 16).

3.6 DATA CAPTURE AND ANALYSIS

'Data' refers to the unprocessed information that researchers gather from research participants (Fraenkel et al., 2012). Once data has been collected the researcher needs to capture it, organise it, analyse it, and then interpret it.

3.6.1 Capturing the data

The data from the written paragraphs in the diagnostic activity in my study were copied word-for-word into a Microsoft Excel spreadsheet. I decided to use the Excel software programme to capture, analyse and store the data, because it captures data in a condensed format; facilitates organising and counting data, allowing for "count if" searches; permits calculations using macros; and has inbuilt functions for performing the more common statistical tests.

The data from the interviews was initially on audio file. To aid data analysis this was converted into text by the process of transcription (as advised by Creswell, 2012). A transcriptionist was used for this process. Each transcription was checked for accuracy by listening to the tapes and making necessary corrections, as advised by Bathmaker (2004). Once the corrections were made, a copy of each interview recording and transcript was stored in the form of electronic files, with the students' codes as the reference to retain anonymity and confidentiality.

3.6.2 Organising the data

Organising data is an important early step when managing large amounts of data (Creswell, 2012). The aim of organising the data is to separate it into "workable units" (McMillan & Schumacher, 2010, p. 369) so that it does not become overwhelming, and to aid the data analysis process (McMillan & Schumacher, 2010). Both Creswell (2012) and Bathmaker (2004) note the value of organising, storing and analysing data in computer files, with the latter making use of a data organisation and analysis software programme. I organised the data for each diagnostic activity question on a separate sheet in a Microsoft Excel workbook.

3.6.3 Analysis of the data

According to Cohen et al. (2005, p. 147) data analysis in social research involves the process of "organizing, accounting for and explaining the data; in short, making sense of the data in terms of the participants' definitions of the situation, noting patterns, themes, categories and regularities". The entire research project stands or falls on the quality of the data analysis, as "shoddy, ill-conceived or inappropriate data analysis can render an otherwise sound research project worthless" (Opie, 2004, p. 130). I therefore took a number of steps to improve the reliability and validity of the analysis. I read up on data analysis strategies during the planning stage of the research project, to develop a clear strategy that would be more likely to yield valid results, as advised by Opie (2004).

Many educational researchers look for patterns using a data analysis technique called 'coding'. The development of a coding scheme helps to ensure that all of the data is scored using the same set of procedures and criteria to avoid "erroneous or misleading results" (Fraenkel et al., 2012, p. 140). Coding is the process of dividing the data up into segments that stand alone or into units that are comprehensible by themselves (Creswell, 2012; McMillan & Schumacher, 2010). A code is defined as a "name or a phrase that is used to provide meaning to the segment" (McMillan & Schumacher, 2010, p. 371). A code can be an activity, phrase, word, quote or process (McMillan & Schumacher, 2010), but it is important that the code and the category from which the code comes be explicit so that another researcher can code the same set of data and achieve similar results (Fraenkel et al., 2012). These segments are usually then assigned an abbreviated code to facilitate the analysis process.

Codes can be derived from existing categories in the literature or they can be constructed by the researcher as the analysis progresses, a process known as open coding (Zhang & Wildemuth, 2005). I used both processes. The first category of codes was derived from a memorandum of the correct scientific explanations for each of the open-ended questions. Each of the memoranda was face validated by two university academics, the first an expert in evolution education, and the second an expert in evolutionary biology. Codes of the concepts considered vital for a correct explanation were developed for each of the questions, and each student's written response was scrutinised for the inclusion of these concepts. The coding categories for identifying unscientific ideas, and the use of anthropomorphic and teleological wording were initially derived from the literature, but I added new codes and categories as the coding process proceeded and new categories of answers emerged from the students' responses. During the development of the coding scheme, as the list of codes developed, I started looking through the students' answers to identify addition points not in the initial coding scheme that had been based on the literature. I also examined the coding scheme periodically and looked for possible duplication and redundancy, removing or joining codes where necessary (as advised by Creswell, 2012). Codes were then grouped into categories according to a common theme or pattern (e.g. correct answers, unscientific ideas associated with the evolution on demand alternative framework, other unscientific ideas, types of thinking, terms commonly used in the explanations [whether faulty or desired]). Under "unscientific ideas" I looked particularly at who/ what students said were adapting, how long they said the process took, and what they identified as the cause of the adaptive process. Using the developed coding scheme I then started from scratch to code the students' answers. The codes used to analyse the diagnostic activities were also used to analyse the data from the interview. The categories and codes discussed in this section therefore apply to both the pre- and post-diagnostic tests and the pre- and post-instruction interviews (see Appendix D for the coding scheme for the explanation questions).

Two methods were used to come to terms with the data in this study, namely pattern identification and frequency counts. A pattern is a perceived relationship between categories of codes (McMillan & Schumacher, 2010). McMillan and Schumacher (2010, p. 485) suggest that identifying patterns is the means through which the end goal of qualitative research, namely the formation of “general statements about relationships among categories”, can be achieved. It is imperative that each pattern identified in the data be “reasonably supported by the data” (McMillan & Schumacher, 2010). The pattern of most interest to this study is the relationship between students’ understanding of adaptation before and after learning about natural selection. Once codes have been determined, Fraenkel et al. (2012, p. 485) believe that the “end product of the coding process must be numbers”. Frequency counts of the codes were conducted to determine the prevalence of correct concepts in the explanations, as well as the extent of unscientific ideas and ways of thinking. Frequency counts were then used to perform statistical analyses of the pre- and post-instruction frequency counts.

Statistical analyses

The selection of statistical tests depends on two factors. Firstly, the selection of a statistical test will depend on the types of data gathered in the study. Secondly, the statistical test selected will depend on the researcher’s motivation for using statistical analysis. If the researcher merely wants to describe the sample statistically in terms of the mean, median, standard deviation etc. the researcher will make use of descriptive statistics. If the researcher desires to make inferences about the population as a result of the data collected from the sample, the researcher will make use of inferential statistics.

Data can either be continuous or discrete. Continuous data has any possible value between two other values. A person’s weight is hardly ever exactly 35 or 36kg. It could be anywhere between 35.01 to 35.99. Discrete data is data that can only have specific values. The number of children in a classroom, for example, can only be 25 or 26. It cannot be 25.33 or 26.56. Four ‘levels’ of measurement of data also exist and are explained, in Table 15, in order of sophistication beginning with the most primitive.

Inferential statistical analyses were performed on the data in this study to see whether the differences between frequencies were statistically significant or were likely to have been a matter of chance. Parametric tests are generally more powerful than non-parametric tests. Power, in statisitics, refers to the probability that the test will lead to the correct conclusion, i.e. “that there is a difference when, in fact, a difference exists” (Fraenkel et al., 2012, 239).

To use parametric tests the data should have a normal distribution around the mean (Fraenkel et al., 2012). Non-parametric tests should be used when the data that does not have a normal distribution. While it is widely recognised that parametric tests cannot be used unless the data is normally distributed, some authors (for example: Kuzon, Urbanchek, & McCabe, 1996; Zar, 2010) argue that the sample should also be randomly selected, with a sample of 30 or more. Norman (2010, p. 625), however, argues that “parametric tests are robust with respect to violations of these assumptions”.

Robustness refers to the likelihood that the test will continue to provide the ‘right’ answer even if certain assumptions are violated. This is particularly relevant to this study, where the sample was not randomly selected and the data for some questions had a skewed distribution (for example, see Figure 10, Section 4.1.2, p. 72). In my study, I have both nominal data and ratio scale data, so I made sure that I used the appropriate tests.

Table 15: Types of data (based on Zar, 210, p. 2-4)

Type of data	Explanation
Data in nominal categories	Data classified by name or a descriptor rather than a number (though a number may be used to represent a category). In my study I counted the frequency of correct ideas and unscientific ideas as represented by codes (e.g. C1, C2 etc.). Only non-parametric tests can be used as a statistical measure for nominal data (e.g. mode, frequencies).
Data on an ordinal scale	The data is nominal, but deals with relative differences rather than numerical or quantitative differences. It is distinct from nominal scale because it has a ranking scale. For example, students might be asked to rate their understanding of the topic of adaptation as excellent / Good / average / weak / poor. Statistical tests include those for nominal data and Chi-square, u-test.
Data on an interval scale	Interval data has constant interval sizes between numbers but does not have a true zero point. Examples include: temperature and time (the zero point in arbitrary). For example, comparing the length of time taken for each student to complete an instrument. Both descriptive statistics and parametric statistics can be used with interval scale data. Tests include those for nominal and ordinal data as well as t-tests and z-scores.
Data on a ratio scale	As for interval scales, a constant interval exists between measurement units on the scale, but ratio scale data must have a true zero point. This helps with establishing meaning when comparing the ratio of variables. Fraenkel et al. (2012) note that ratio scale data is hardly ever found in educational research. All statistical tests can be used with ratio-scale data.

The sorts of tests used for different purposes in my study are summarized in Table 16.

Table 16: Statistical tests used in this study, and the data upon which they were used

Data	Purpose of analysis	Statistical test
Nominal data	To determine the frequency of use of correct scientific ideas pre- and post- instruction.	Frequency counts, descriptive statistics such as means
Ratio-scale data	To determine whether the difference in pre- and post-instruction **mean scores** are statistically significant	Paired t-tests
Nominal data	To check the statistical significance of differences in pre- and post-instruction frequencies of **each concept held**, for the whole group.	McNemar Chi^2
Nominal data	To determine the frequency of use of scientific and unscientific ideas pre- and post- instruction	Frequency counts

Paired sample t-test

The paired sample t-test helps the researcher determine whether the observed differences between the pre- and post-instruction group means are statistically significant. I used this where I wanted to check whether the students’ pre- and post-instruction mean scores were significantly different (for their knowledge of adaptation and their unscientific ideas). Paired-sample t-tests are used when the two variables being compared are dependent, like when the same group supplies the data (as is the case for pre- and post- measurements). In this study, the same group supplied the data before and after the section on evolution was taught in Grade 12. In other words, there is a “pairwise association of the data from the two samples” (Zar, 2010, p. 181). The paired sample t-test was looked at as a one tailed paired t-test because the direction of the change was expected to be positive moving from pre- to post-instruction. Two-tailed tests are used only when the direction of the expected change is not known.

McNemar test

The χ^2 (Chi^2) or “goodness of fit test” (Samuels & Witmer, 1999; Zar, 2010) is used to check the likelihood that a set of observed values meets the theoretically expected values when the data is nominal or ordinal (Zar, 2010). In this study, the McNemar variation of the chi-squared test was used because nominal data was gathered both before and after instruction, which means that I have a dependent sample. By using the McNemar variation of the χ^2 I was able to assess statistical differences between the same students pre-instruction and post-instruction understanding of adaptation. For this reason, the McNemar χ^2 is sometimes referred to as the “repeated measures chi-squared” (Zar, 2010). In this study, the nominal data for correct and unscientific ideas was recorded as ‘present’ or ‘absent’. For each correct concept mentioned in students’ answers before instruction, a ‘yes’ was placed in the relevant column. For each incorrect (unscientific) idea, a ‘no’ was placed in the relevant column before instruction. This same process was used for students’ post-instruction responses. Because this was a pre- and post-instruction study, there were four possible variations in students’ pre- and post-instruction answers, two discordant (yes/no; no/yes) and two concordant (yes/yes; no/no) pairs (Samuels & Witmer, 1999). The McNemar χ^2 makes use only of a 2x2 contingency table, that only compares only the discordant pairs. The concordant pairs are considered to be ‘tied’ and are discarded in the calculations (Zar, 2010).

The McNemar variation of the χ^2 is used to determine how likely it is that the difference between the pre-instruction and post-instruction scores occurred by chance. The McNemar χ^2 provides an actual *p* value. A *p* of 0.05 or lower is a good indication that the difference between the paired scores is significant (Samuels & Witmer, 1999). I used an internet-based McNemar test found at the following URL: http://scistatcalc.blogspot.co.za/2013/11/mcnemars-test-calculator.html.

Apart from my reading of the literature, I consulted two senior lecturers with knowledge and experience in teaching statistics to undergraduate and post-graduate students for help on which version of the χ^2 to use. A third researcher with many years of experience teaching research methodology to post-graduate students checked my results for accuracy.

3.7 IMPROVING THE RESEARCH RIGOUR

‘Rigour’ is “the quality of being extremely thorough and careful” (Oxford University Press, 2017) and is important in establishing the soundness or “goodness of research” (Opie, 2004). To improve the rigour of this study, matters of reliability and validity were considered throughout the development of the instruments, the analysis of the data, and as inferences were made about the data. While reliability and validity are independent facets in determining sound research, they are also “bound together in complex ways” (Creswell, 2012, p. 159). Creswell (2012) notes that if scores from the instrument are not reliable they will not be valid. The more reliable the scores of an instrument are, the more valid the scores are.

Reliability therefore influences validity. The ideal situation is to have scores that are both reliable and valid (Creswell, 2012).

3.7.1 Reliability

Reliability refers to the consistency and replicability of research over time (Cohen et al., 2005; Opie, 2004). Scores need to be stable when an instrument is administered on repeated occasions at short intervals (Creswell, 2012, p. 159). In this respect reliability is concerned with accuracy and precision (Cohen et al., 2005; Leedy, 1989). If the same instrument were to be administered on a different day similar results should be achieved, providing other variables are controlled for. Random factors can influence reliability: e.g. the time of day; energy levels of the respondents; testing environment and situation; and anxiety or stress levels (Fraenkel et al., 2012). Where possible these should be controlled by the researcher. Factors such as the administration of the instruments and data capture and analysis should be kept consistent to improve reliability.

The following steps were taken to improve reliability during the study:

1. Steps were taken to ensure the administration of the pre- and post-instruction diagnostic test was consistent between the three schools. While the activities were administered at different times in the day, different days of the week, and by different class teachers, the process of administering the activities was standardised. I issued each teacher a list of instructions (as advised by Cohen et al., 2005) for the administration of the activity and I verbally explained the procedure to each teacher (e.g. to be completed under test conditions, Part 1 handed out and collected in before Part 2 is handed out, etc.) (See Appendix C for the instructions).
2. Once all the data from the diagnostic activities had been collected, it was captured word-for-word into a Microsoft Excel spreadsheet. A second person checked the accuracy of the data captured from the activities. A second person also checked the accuracy of the transcription of the interviews by listening to the audio-recordings and reading the transcriptions concurrently.
3. To improve the inter-coder reliability of the data analysis a second coder coded the data from activities and the interviews. Fraenkel et al. (2012) note that high levels of agreement between two coders in a study increases the reliability of the study. For reliability to be at an acceptable level, it is generally accepted that 80% agreement must be achieved (Fraenkel et al., 2012). In this study only 100% reliability was deemed ’acceptable’. Any discrepancies between the coders were discussed until full agreement was achieved. In a few instances, coding the latent or ‘not so obvious’ meanings in written answers was ambiguous and the two coders came to different conclusions about what the student meant. For example, when students referred to ‘animals’ or ‘organisms’ in the plural, trying to ascertain whether the students were referring to the population or just a few individuals within the population proved difficult. In such cases the answers in question were taken to a third lecturer for an opinion, and her viewpoint was used as the correct code to apply.

3.7.2 Validity

Validity is regarded as being the “single most important aspect of an instrument and the findings that result from the data” (McMillan & Schumacher, 2010, p. 178). There are two components to validity that researchers need to demonstrate that they have paid attention to, namely the validity of the results obtained from the research instruments, and the validity of the inferences made by the researcher (Fraenkel & Wallen, 1990; Sanders & Mokuku, 1994). While perfect validity is seldom attainable, a researcher should pursue it in an effort to provide useful, appropriate, meaningful and useable conclusions (Fraenkel et al., 2012).

The format of the instrument has the potential to influence the validity of the results obtained from the instrument (Gall et al., 1996; McMillan & Schumacher, 2010). Fraenkel and Wallen (1990, p. 129) note that the format of instruments is as important as the questions themselves, pointing out that “regardless of the adequacy of the questions in an instrument, if they are presented in an inappropriate format, valid results cannot be obtained”. With regard to the diagnostic activity, such things as font size and type, clarity of the printing, appropriateness of the language, clarity of the instructions, and quality of the test environment could all have affected validity (Fraenkel et al., 2012).

A number of facets in this project went through the process of face validation (discussed in section 3.4.1, p. 47):

- The design of the pre- and post-instruction diagnostic activities was face validated by a professor in science education with expertise in both evolution education and research methodology, having taught courses in both areas to postgraduate students (discussed further in section 3.4.1, p. 47).
- The interview schedules were face validated by a professor who is considered an expert in science education and research methodology (see section 3.4.2, p. 54).
- The accuracy of data capture and frequency counts, and correct use of the “count if” macros, were checked by the science education and research methodology expert already mentioned, to ensure no errors had crept in
- A biology professor and teacher of senior evolution courses considered to be an expert in evolutionary biology, and a professor in science education with particular teaching interests in evolution education, checked the scientific correctness of the model answers used for coding correct scientific answers for the questions on the pre- and post-instruction diagnostic activities (see section 3.6.3, p. 60).

Other aspects of validity were also checked:

- Each transcription of the pre- and post-instruction interviews was checked for accuracy by listening to the recording and reading the transcript concurrently (see section 3.6.1, p. 59).
- Advice on how to conduct the paired t-tests and the McNemar variation of the Chi^2 test was obtained from a retired staff member now appointed as an honorary senior lecturer, and a professor in our school (Animal Plant and Environmental Sciences) who is an expert in statistical data analysis and who runs post-graduate courses in statistics.
- Inferences made from the data analysis were checked by a professor in science education with particular teaching interests in evolution education.

Every effort has been made to improve the validity of both the research instruments and the inferences derived from the data collected by the instruments, as this section has sought to show.

3.8 ETHICAL CONSIDERATIONS

Researchers have a moral obligation to conduct their research in a responsible manner that respects the rights and freedom of those being asked to participate in the study (Cohen et al., 2005; McMillan & Schumacher, 2010). This is particularly true with research that requires more (in terms of time, effort etc.) from the research participants (McMillan & Schumacher, 2010), as was the case in this study. I took a number of steps to ensure compliance with the ethical standards of educational research, as required by the University of the Witwatersrand.

3.8.1 Obtaining permission to conduct the study

Permission was obtained from three groups of stakeholders. Firstly, I obtained permission from the Human Research Ethics Committee (Education) at the University of the Witwatersrand, to conduct research. I put together an ethics application, which was approved by the committee - protocol number 2016ECE028M (see Appendix E for the Ethics Clearance letter). Secondly, permission was obtained from the principals at the three schools where the research took place. Before I obtained permission, I explained the research and promised each of the principals that the names of their schools and their students would remain anonymous and that consent would be gained from both parents and students before including students in the final sample. Written permission was obtained from the principals at all three schools. Finally, a meeting was held with each of the Life Sciences teachers at the three schools, at which time I explained the research project. I also issued a letter to each teacher explaining the purpose of the project. Each teacher verbally expressed their willingness to be involved in the project. My contact details were included in case teachers had any concerns or questions that they needed to ask me about.

3.8.2 Full disclosure to potential student participants

All students completed the pre- and post-instruction diagnostic activities as a part of the normal teaching and learning process. Students were not informed about the diagnostic activity or of its purpose, before completing it. Once the students had completed the pre-diagnostic activity the research project was verbally explained to each class of students before participation was solicited by asking whether their answers could be used for my study. Students were informed about the purpose of the research, what being involved would require them to do, that participation in the research project was voluntary, and that no student would be named or described in any identifiable way (promise of anonymity) in the write up of the project. Each student received a letter summarising what he or she had been told. Because the students were under the age of 18 at the time, students were also given an information letter to take home to their parents. The letter outlined the purpose of the research project, and the same points already made to their children (see Appendix F for a generic example of an information letter). The information in the letter was sufficiently broad so that neither the students nor their parents were aware that adaptation was the topic of interest in the project. Students at the school where I teach were also asked to take part in a pre- and post-instruction interview. The letter that was sent home to these students, and a similar letter to the parents of the students, informed the students / students’ parents that their participation in the interviews was voluntary and that the students' names would be kept confidential

3.8.3 'Informed' consent

Once students had been informed of the research project, and their participation solicited, I sought their written consent to take part in this research project. A consent form, attached to the information letter, was sent home with each student. I asked students to indicate their consent by signing the consent form and returning it to their teacher. Parental consent was requested from each student under the age of 18. Only students who returned both their own and their parents' consent forms were included in the sample for the study.

3.9 CONCLUDING REMARKS

This chapter has outlined both the theory behind, and the practical application of, the methodological procedures used in this study. To understand the importance of natural selection to the understanding of adaptation, it was necessary to first find out what students knew about the topic of adaptation before learning about natural selection. This was important, considering that the topic of adaptation is frequently taught in the grades leading up to Grade 12. Interviews were then conducted with students from one school to probe their answers and to find out how strongly they held their scientific / unscientific ideas. The post-instruction activity was then administered to assess whether students' understanding of adaptation had improved after learning about natural selection. Interviews were held with the same students that were involved in the pre-instruction interviews, to explore their ideas about adaptation after learning about natural selection. Students' pre- and post-instruction scores were then compared using various statistical procedures to establish the significance of difference between pre- and post-instruction scores of group means, and categories of scientific and unscientific ideas. Due consideration was given to improving validity and reliability of the data-gathering instruments, data capture and analysis, and the inferences derived from the data. Standard research protocols were followed to ensure that the research was conducted ethically. In Chaper 4, I present the results and a discussion of these results for this study.

Chapter 4

Results and discussion

To answer the main research question in this study, five sub-questions were developed. The answer to each of these sub-questions will together provide the answer to the main research question.

Main research question
What is the nature and extent of Grade 12 Life Sciences students' understanding of biological adaptation, before and after learning about natural selection?

The five sub-questions provide the structure for presenting and discussing the results in this chapter. The findings contained within the chapter are discussed in light of previous literature, summarised in the conceptual framework described in Chapter 2. Figure 9 outlines the content and sequence of the sections in the chapter.

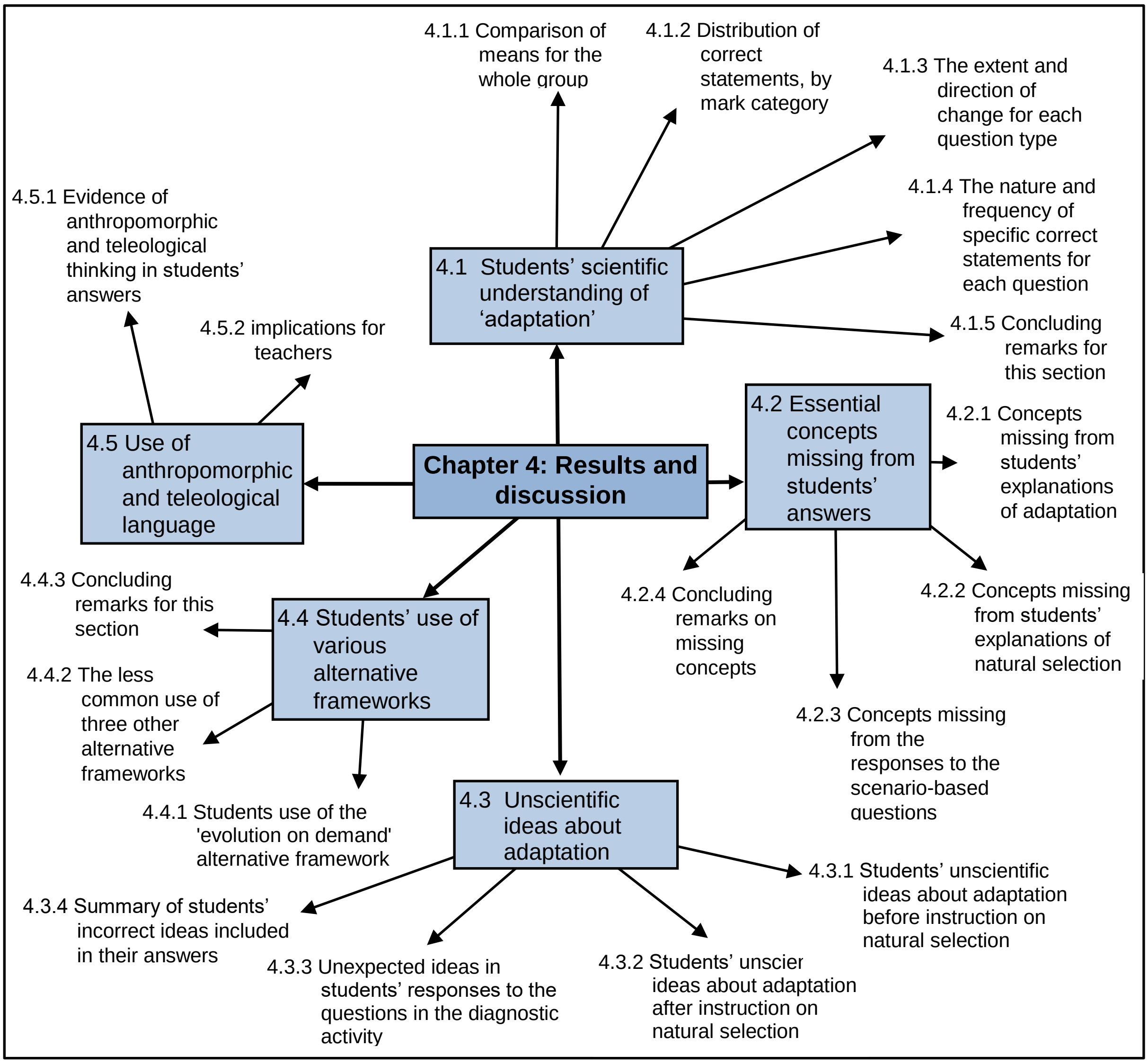


Figure 9: Structure of Chapter 4

In this chapter, the terms 'unscientific idea' and 'misconception' will be used interchangeably to refer to students' ideas that differ from the current scientific understanding. The term 'misconception' will be used in the layman's sense of the word (Wandersee, et al., 1994) because it was not possible to tell whether the unscientific ideas in this study were true misconceptions or acquired errors (see Section 2.4.1, p. 29). The phrases 'pre-instruction' and 'post-instruction' refer to data collected before and after the teaching and learning of the topic of *natural selection*, a section covered in the South African Grade 12 Life Sciences curriculum (Department of Basic Education, 2011b). Understanding *natural selection* is foundational to an understanding of biological *adaptation* (Bock, 1980; Ridley, 2004).

4.1 STUDENTS' SCIENTIFIC UNDERSTANDING OF 'ADAPTATION'

This section answers the first research sub-question. As mentioned in Chapter 2, few studies look into students' **correct** ideas about *adaptation*, and this section aims to fill that gap in the literature. It is important to remember that although pre-instruction ideas are compared with students' ideas after they learn about *natural selection* in Grade 12, no specific intervention was used in this study: teachers were specifically asked to teach no differently from how they would normally have taught the section.

Question a: What is the nature and extent of the scientific concepts about biological *adaptation* held by the students, before and after learning about *natural selection*?

Students' scientific understanding was assessed using diagnostic activity questions at two levels of Bloom's taxonomy of cognitive objectives. The open-ended questions in the second section of the diagnostic activity, which involved explaining *adaptation* and *natural selection*, were considered to be Level 2 questions (comprehension), because they involved students going beyond simply recalling facts and instead required them to demonstrate an understanding of the facts by explaining their ideas in their own words (see the updated Bloom's taxonomy: Amer, 2006; Krathwohl, 2002). The open-ended questions in the first section of the diagnostic activity were considered to be Level 3 questions (application) because they required students to apply their knowledge to unfamiliar situations. Students' understanding was assessed against a memorandum with correct statements that three experts had considered to be important for an explanation of the two terms. The correct answer for the Level 2 (comprehension) questions included six scientific statements (see Table 20 and 21). The Level 3 questions (application) included eight scientific statements (see Table 22) that were needed for an answer to be judged fully correct.

The purpose behind the analysis of data is so that patterns, themes, categories and trends within the data can be found (Cohen et al., 2005). To answer research sub-question a, the data was analysed in several ways, starting with a general overview of the data in terms of group scores and then progressively looking at the data in more and more detail, and eventually for specific clusters of students and for specific answers.

4.1.1 Comparison of means for the whole group

Table 17 summarises the total number of correct statements given by the group, for each question and for the whole instrument, pre- and post-instruction. Each student was awarded a mark out of 28 for their answers (8 + 8 for the two scenario-based questions, and 6 + 6 for the two explanations).

Almost twice as many correct statements were given by the group for the diagnostic activity after the teaching of natural selection than before: The total number of correct statements supplied by the group before instruction was 294 out of a possible 2520 (28 marks for each of the 90 students) compared with 570 correct statements provided by the group for the post-instruction instrument. A paired t-test showed that the difference was statistically significant ($p = 0.03$). This alone is an important finding, that even without a specific intervention simply learning about natural selection significantly improves students' understanding of the concepts associated with evolutionary adaptation, as was found by Bishop and Anderson (1990), Engel Clough and Wood-Robinson (1985a), Jensen and Finley, (1996), Schroder and Dempster (2014), and others. However, the average number of correct statements per student for the pre-instruction instrument was only 3.27 out of 28. The average number correct per student for the post-instruction test was 6.3 out of 28. Although this score doubled, it still shows a very poor understanding of natural selection.

Table 17: Number of correct statements for the pre- and post-instruction instruments, by question

Pre-instruction				**Post-instruction**			**t-test**
Question	**Total correct points needed**	**No. of correct statements supplied by the group**	**Mean correct statements per student**	**Question**	**No. of correct statements supplied by the group**	**Mean correct statements per student**	***p* =**
Comprehension level questions (explanation of terms)							
1. adaptation	6	120	1.33	1. adaptation	127	1.41	0,28
2. natural selection	6	13	0.14	2. natural selection	68	0.76	0.004x10^{-5}
Total: explanations	12	133	1.48	Total: explanations	195	2.17	
Application level questions (scenario-based questions)							
3. moth	8	110	1.22	3. beetle	202	2.24	0.003x10^{-3}
4. elephant	8	51	0.57	4. seal	173	1.92	0.001x10^{-6}
Total: scenarios	16	161	1.79	Total: scenarios	375	4.17	
Total correct statements	**28**	**294**	**3.27**	**Total correct statements**	**570**	**6.33**	**0.034**

Students provided more correct statements about adaptation than natural selection, for both the pre- and post-instruction diagnostic activity: Comparing the two pre-instruction explanations, the total number of correct statements given by the group of students was ten times higher for *adaptation* (120 correct statements) than for *natural selection* (only 13 correct statements from the whole group), giving correspondingly higher mean correct statements per student (1.33 for *adaptation* and only 0.14 for *natural selection*). Students' post-instruction answers also showed more correct statements for *adaptation* (127 correct statements) than for *natural selection* (68 correct statements), giving correspondingly higher mean correct statements per student (1.41 for *adaptation* and 0.76 for *natural selection*). Students may have a better understanding of adaptation because they have learnt about it in previous grades (see Section 1.3, starting on p. 5), and because students generally struggle to understand the topic of natural selection (Bishop & Anderson, 1990; Settlage, 1994; Tamir & Zohar, 1991; Yates & Marek, 2015).

While the total number of correct statements about adaptation (pre- and post-instruction) remained about the same, the total number of correct statements about natural selection improved five-fold: The total number of correct statements provided by the group in their explanations of *adaptation* did not change-significantly ($p = 0.28$) from pre- to post-instruction (120 before and 127 after). There were five times more correct statements for *natural selection* after instruction (from 13 pre-instruction to 68 post-instruction). This difference was statistically significant ($p = 0.004\text{x}10^{-5}$). It is important to bear in mind when looking at these results that the students had just been taught about *natural selection*, but that *adaptation* was not specifically addressed, although the term *adaptation* would have been used in lessons.

The students' answers appeared to be affected by the context of the scenario-based questions: When I did the coding I noticed that, as Engel Clough and Wood-Robinson (1985a) had found, the context of the question appeared to influence students' responses. For example, for the two pre-instruction scenarios, students provided twice as many correct statements for the insect (peppered moth) question than for the mammal question (elephant). A similar trend was found in students' answers to the fruit chafer beetle and seal questions in the post-instruction instrument, although the difference in the number of correct statements between the scenario-based questions was not as great as that on the pre-instruction instrument. The elephant question, involving the regulation of body temperature, was the least well answered of the four scenario-based questions. Students' tended to get side tracked by the issue of global warming (24 students mentioned it as a problem) and its effect on elephant evolution, and this may have distracted students from answering the actual question. Therefore, if students' answers depend on the scenario in the question, giving students only one question to answer in a diagnostic activity might raise doubts about the validity of the assessment as a measure of students' understanding.

Significant improvements were seen in the frequency of correct statements for the application (scenario-based) questions after instruction: The frequency of students' correct ideas for the 'insect' question nearly doubled from pre- to post-instruction (from 110 for the peppered moth to 202 for the fruit chafer beetle), and more than tripled for the mammal question (from 51 for the elephant question to 173 for the seal question), both sorts of scenario-based questions giving statistically significant increases of $p = 0.003\text{x}10^{-3}$ and $p = 0.001\text{x}10^{-6}$ respectively. This shows that learning about *natural selection*, even without a specific intervention, seemed to have improved students' ability to apply that knowledge in the scenario-based questions, for the post-instruction activity. However, the mean number of correct statements per student was still very low, and caused by students' poor knowledge of the mechanism of adaptation, natural selection.

4.1.2 Distribution of correct statements, by mark category

The previous section dealt with the frequency of correct statements before and after instruction. This section provides a more nuanced view of the groups' performance by presenting the number of correct statements in 'mark categories'. Post-instruction changes are revealed most clearly when the data is shown graphically (see Figure 10) whilst Table 18 (following the graphs) provides more detailed information.

Distribution of correct statements for the whole group

Generally, a shift upward, toward highter marks categories, occurs in the distribution before and after the teaching of natural selection (see Figure 10).

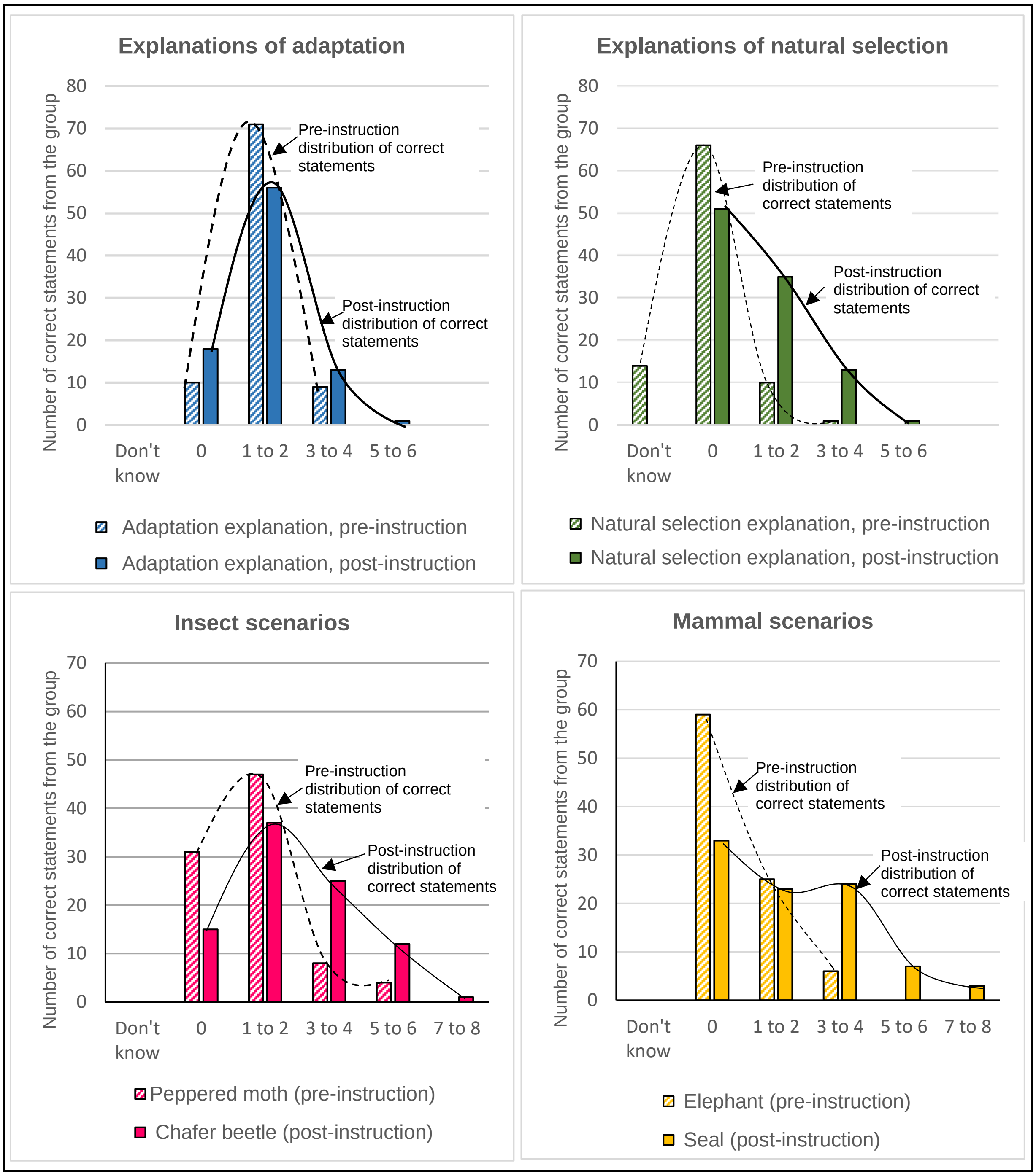


Figure 10: Students' performance as the total number of correct statements per marks category

The trend lines on the graph serve to highlight the shift in the categories of students' responses from pre- (dotted line) to post- (solid line) instruction answers. The distribution of correct statements from pre- to post-instruction shifts decisively to the right in each graph, though only a small shift occurred for the *adaptation* explanation.

The data from which the four graphs in Figure 9 were drawn is shown in Table 18, and indicates the frequency of students in each mark category, by question, pre- and post-instruction. The last column in the table shows the percentage increase or decrease for each category from pre- to post-instruction. It is important to keep in mind when looking at the data in Table 18 that fewer students in the low-scoring categories, and more students in the higher scoring categories indicates progress in understanding. The reverse would indicate a lack of progress or regression in student understanding. While some positive trends emerge from the data, there is cause for concern, particularly about the teaching and learning of natural selection.

Table 18: Summary of students' performance by mark category (n = 90)

Pre-instruction			Post-instruction			
Question	**No. of correct ideas**	**No. of students (%)**	**Question**	**No. of correct ideas**	**No. of students (%)**	**% increase or decrease**
Explanation of terms (comprehension level questions)						
adaptation	*Do not know* or *no answer*	0 (0%)	adaptation	*Do not know* or *no answer*	0 (0%)	0
	0	10 (11%)		0	18 (20%)	9% ↑
	1-2	71 (79%)		1-2	58 (65%)	14% ↓
	3-4	9 (10%)		3-4	13 (14%)	4% ↑
	5-6	0 (0%)		5-6	1 (1%)	1% ↑
natural selection	*Do not know* or *no answer*	14 (16%)	natural selection	*Do not know* or *no answer*	0 (0%)	16% ↓
	0	65 (73%)		0	50 (56%)	17% ↓
	1-2	10 (11%)		1-2	35 (39%)	28% ↑
	3-4	1 (1%)		3-4	3	2% ↑
	5-6	0		5-6	2	2% ↑
Scenario-based questions (application level questions)						
peppered moths	*Do not know* or *no answer*	0	fruit chafer beetles	*Do not know* or *no answer*	0	0
	0	31 (34%)		0	15 (17%)	17% ↓
	1-2	47 (52%)		1-2	37 (41%)	11% ↓
	3-4	8 (9%)		3-4	25 (28%)	19% ↑
	5-6	4 (5%)		5-6	12 (13%)	8% ↑
	7-8	0		7-8	1 (1%)	1% ↑
elephants	*Do not know* or *no answer*	0	seals	*Do not know* or *no answer*	0	0
	0	59 (65%)		0	33 (36%)	29% ↓
	1-2	25 (28%)		1-2	23 (26%)	2% ↓
	3-4	6 (7%)		3-4	24 (27%)	20% ↑
	5-6	0		5-6	7 (8%)	8% ↑
	7-8	0		7-8	3 (3%)	3% ↑

Percentages have been rounded off to the nearest whole number

Trends in students' pre- and post-instruction explanations of adaptation and natural selection

Before instruction, there is an observable difference between the numbers of students who recorded a 'do not know' answer for natural selection (16%) compared with adaptation (0%): I surmise that this is largely down to the students' familiarity with the topic of *adaptation* from previous grades and their lack of familiarity with the topic of *natural selection*. The number of students who recorded a 'do not know' answer after instruction remained the same for *adaptation* (0%), but declined to zero percent for the *natural selection* explanation. Students felt confident enough to provide an explanation for both *adaptation* and *natural selection* after instruction on natural selection.

While every student provided an explanation for adaptation and natural selection after instruction, the number of correct statements contained within answers did not necessarily improve**:** When comparing students' post-instruction explanations of *adaptation*, 9% fewer students 'did not attempt to answer' the question, but only 5% of students moved up to the highest two mark categories. Fewer of the students who gave answers had 'no correct ideas' in their explanations of *natural selection* after instruction (56% of the group) than before (73%), an improvement of 17% (n = 15). Many students moving up from the 'I do not know' and '0' categories now had one or two correct statements' for the *natural selection* question, an increase of 28% (n = 25) Students with 'three or four correct statements' and 'five and six correct ideas' for the *natural selection* question increased by only 2% (n = 2). While improvements were seen in the number of correct statements in many students' explanations of *natural selection*, this does not necessarily translate into an improvement in students' understanding of *adaptation*. For example, after instruction student GT15 mentions four correct ideas when explaining *natural selection*, but still did not appear to have a full understanding.

> "Natural selection happens when <u>there is a variation in a population</u> living in an environment. The environment could be <u>favourable to one particular group,</u> <u>making them superior in number</u>. However, the environment could be <u>non-favourable to many and they could then decrease in number</u>, making the superior/favourable group in reproducing more of themselves". (GT15)

This student's partial understanding of *natural selection* is probably because of being taught the topic, considering that this student achieved zero out of six for the pre-instruction explanation of *natural selection*. However, when explaining *adaptation* the student does not show the same improvement. While she changes the explanation, she is no closer to being correct.

Before instruction:

> "Adaptation is something you adapt to along the way. You are not born with it, you adapt to it mainly due to your surroundings eg. Weather or pollution" (GT15).

After instruction:

> "Adaptation is when an environment a natural cause takes place (sic) which then shifts the organisms which were living in the environment into other areas. Leading them to adapting to the environment they have now been exposed to" (GT15).

This student has not understood the close relationship between *adaptation* and *natural selection* (discussed in Section 1.1 of Chapter 1) and does not explain *adaptation* in terms of *natural selection*.

Trends in students' pre- and post-instruction responses to the scenario-based questions

Fewer students had two or less correct ideas for the scenario-based questions after learning about natural selection**:** Twenty-eight percent fewer students in the group had only this small number (1–2) of correct statements in their answers to the two <u>insect</u> questions (86% of the group pre-instruction, to 58% post-instruction) and a decrease of 31% occurred between the percentage of students with only 'one or two correct statements' in their answers to the two <u>mammal</u> questions (93% pre-instruction, to 62% post-instruction).

More students provided five or more correct ideas in their responses: There was a 9% increase in the percentage of the group with '5-6' correct statements in their answers to the insect questions and an 11% increase in the mammal questions. This suggests that instruction on *natural selection* improved students' ability to explain how *adaptation* occurs in populations of organisms even though students battled to explain the concept of *adaptation* on its own. The only student in the "7-8 correct ideas" category for the fruit chafer beetle scenario-based question said:

> In the population of the fruit chafer beetles there was variation between those that were yellow and [those that were] emerald in colour. There were few emerald chafer beetles before the drought, but after the drought they increased in number. This was because the yellow beetles were no longer camouflaged on leafy acacia trees and began to die out and reproduce less frequently. Whilst the emerald beetles would survive and reproduce passing the characteristics to the offspring and increasing the amount of green beetles in the population (GT14).

This student identifies seven of the eight criteria needed for a correct and complete answer to the fruit chafer beetle scenario-based question, missing only the idea that the process of *adaptation* takes generations to occur (see section Table 20, p. 77).

4.1.3 The extent and direction of change for each question type

Another way of illustrating change (improvement or regression) in students' answers after instruction is to show how many students improved their answers by one, two, three marks etc. and how many students regressed by one, two, three marks etc. Table 19 highlights the frequency of students who improved or regressed and the extent of the improvement or regression, for each question. Table 19 presents a negative picture with regards to some students' regressed understanding of *adaptation* after being taught *natural selection*.

Table 19: The extent and direction of change for each question before and after instruction

Adaptation				Insect scenarios			
Additional number correct		Reduction in number of correct ideas		Additional number correct		Reduction in number of correct ideas	
+1	21 (23%)	-1	25 (28%)	+1	19 (21%)	-1	12 (13%)
+2	6 (7%)	-2	8 (9%)	+2	13 (14%)	-2	6 (7%)
+3	1 (1%)	-3	0	+3	10 (11%)	-3	3 (3%)
+4	2 (2%)	-4	0	+4	6 (7%)	-4	0
+5	0	-5	0	+5	4 (4%)	-5	0
+6	0	-6	0	+6	1 (1%)	-6	0
+7	0	-7	0	+7	0	-7	0
No change	27 (30%)			16 (18%)			
Natural selection				Mammal scenarios			
+1	19 (21%)	-1	4 (4%)	+1	20 (22%)	-1	6 (7%)
+2	10 (11%)	-2	0	+2	11 (12%)	-2	1 (1%)
+3	2 (2%)	-3	0	+3	10 (11%)	-3	1 (1%)
+4	1 (1%)	-4	0	+4	5 (6%)	-4	0
+5	2 (2%)	-5	0	+5	2 (2%)	-5	0
+6	0	-6	0	+6	4 (4%)	-6	0
+7	0	-7	0	+7	1 (1%)	-7	0
No change	52 (58%)			29 (32%)			

The number of students who improved their score by one and two points is exceeded by the number of students who regressed by one or two points: This indicates a certain fluidity in students' explanations of *adaptation* and that they do not automatically associate the topics of *natural selection* and *adaptation*. This is not the case with students' explanations of *natural selection* and the scenario-based questions, which saw large numbers of students improve by one, two, or three points (see Table 19). This adds further credibility to the idea that (as a group) students' understanding of *adaptation* improves after learning about *natural selection*.

Three students mentioned seven or more correct ideas in their responses to the seal post-instruction scenario-based question: Although three of 90 students is a small number, these students showed a considerable improvement in their understanding, two students improving their score by six, and one by seven points (see Table 20). These three students' responses to the post-instruction seal question are shown below:

> "There was a large number of seals. There was variation in the population, where some had the genes that allowed them to stay under water for long and some didn't. There was competition for food. The seals that could stay under water for long were able to hunt for fish deep under the sea and so they survived and may reproduce. The seals that can only stay under water for short periods of time weren't able to get food and therefore, die. Number of seals that could stay under water for long increased. population evolved" (PW23).

Student PW23 provided an excellent explanation for *adaptation* in the seal scenario-based question, including six more correct ideas than in her pre-instruction response to the elephant question, missing only the idea that the process of *adaptation* occurs over numerous generations. Similarly, student PW31 also mentioned seven correct ideas.

> "The food the seals had to source started becoming more scarce at the surface of the water so the seals had to dive deeper. There was variation among the seal population therefore some seals were adapted to diving in deeper waters. They then were able to get food to survive and the ones that were not died. The surviving seals are likely to reproduce and some of their genes may have been passed onto their offspring. The offspring was then able to dive into deeper water for food. The population had therefore evolved and the occurrence of seals that could dive deeper for food increased" (PW31).

Student PW31 mentions six more correct ideas in the post-instruction seal scenario-based question than in the pre-instruction response to the elephant question. This student also missed only the idea that *adaptation* occurs over generations.

Student WSV34 had a slightly different idea for the cause of the *adaptation*.

> "1. The first seals hunted shallow water fish so, they could only stay under water for a short time since that is how their body (and respiratory tract) is designed. Something could have changed like another shallow-fish-eating species moving into the seals environment. The seals now had competition for food and had to move to another niche of the habitat to satisfy their needs for food 3. As they began hunting deeper in the ocean, the seals that could not hold their breathe long enough under water died 4. The ones that could hold their breathe long enough did survive. These seals survived long enough to mate together and reproduce to pass down traits like a larger lung capacity to the next generation. 5. This went on for many generation until today we have seals that can hold their breathes for very longer than the first seals (sic)" (WSV34).

It is interesting that this student sees the need to introduce competition in the form of a new shallow water fish-eating species coming into the environment to initiate *adaptation*. Problematically, some Grade 12 examination memoranda in South Africa require the mention of competition as a precondition to evolution (Reddy & Sanders, 2014). However, competition is not mentioned in the evolutionary synthesis, and renowned evolutionary biologist Douglas Futuyma specifically refutes the idea that competition is needed for evolution to occur (Futuyma, 2009). However, student WSV34 also inappropriately explains teleologically that the seals move to deeper hunting grounds is the result of a 'need' to move. Despite some unscientific ideas remaining in this student's answer, significant improvements were seen from pre- to post-instruction in the student's ability to explain the process of *adaptation* in the scenario-based questions.

4.1.4 The nature and frequency of specific correct statements for each question

The previous section discussed the **extent** of correct statements in the groups' pre- and post-instruction answers to each of the questions. It did not, however, discuss the **nature** of the students' scientific understanding. This section looks at the nature of correct statements in students' answers (including frequencies) for each question, pre- and post-instruction, and discusses the trends observed.

Specific correct statements in explanations of '*adaptation'*

Table 20 shows the six scientific concepts that three experts considered to be important for a correct explanation of the term *adaptation.* These were used to evaluate students' scientific understanding of the term, and the statements have been ranked according to the pre-instruction frequency of students who included the statements. For reasons explained in Section 3.6.3 (p. 60), a McNemar chi-square test was used to test for the significance of difference for the change in students' answers from pre- to post-instruction.

Table 20: Frequencies for each correct statement in students' explanations of adaptation (n = 90)

	Pre-instruction	**Post-instruction**	**Change**	***p* =**
	No. of students including the concept			
Adaptation involves becoming more suited to the environment	67 (74.4%)	54 (60%)	14.4% ↓	0.23
Advantageous characteristics convey a survival and reproductive advantage on individuals with the trait	35 (38.9%)	23 (25.6%)	13.3% ↓	0.12
An adaptation can also be a specific advantageous characteristic (feature/ trait)	17 (18.9%)	33 (36.7%)	16.8% ↑	0.023*
Adaptation is a process that occurs by natural selection	1 (1.1%)	3 (3.3%)	2.3% ↑	0.32
Adaptation occurs in populations of organisms	0 (0%)	8 (8.9%)	8.9% ↑	0.005*
Adaptation takes many generations	0 (0%)	6 (6.7%)	6.7% ↑	0.014*
Total	**120**	**127**		**0.65**
Adaptation as a process, product or both				
Explanations only mentioned adaptation as a **process**		72 (80%)	66 (73.3%)	
Explanations only mentioned adaptation as a **product**		34 (37.4%)	39 (43.3%)	
Adaptation discussed as **both a product and as a process**		26 (28.9%)	31 (34.4%)	
* statistically significant at *p* = 0.05 level				

Three statements were included statistically more frequently after the students had been taught about natural selection. As discussed in section 4.1.1 (p. 69), the pre-to post-instruction differences in total frequency of correct statements in students' explanations of *adaptation* were not statistically significant. However, the frequency of students who mentioned three specific statements did show significant increases. The idea that *an adaptation is an advantageous trait* increased significantly, doubling after instruction. Secondly, after being taught about natural selection, nine percent of the group stated that *adaptation* occurs to populations of organisms, up for 9% of the group, from 0% prior to instruction, a statistically significant difference (*p* = 0.005). Thirdly, the idea that *adaptation takes many generations to occur* was also significantly up, from 0% of the group prior to instruction to 7% after instruction (*p* = 0.014). That the improvement in frequency of these three correct ideas was statistically significant was encouraging. However, more than 90% of the sample still did not include these necessary statements.

Two correct ideas about adaptation declined in frequency after instruction about natural selection, but the declines were not statistically significant: Before instruction three-quarters of the students correctly saw *adaptation* as being about *organisms becoming suited to the environment*. Although there was a small post-instruction decrease (from three-quarters of the students stating this to just under two-thirds) it was not statistically significant. The fact that 60% of the students had the understanding that *adaptation* generally refers to, “some kind of relationship between the organism and something else, that something else usually being the environment” (Ghiselin, 2015) is encouraging.

Prior to instruction, just over a third of students (39%) understood that *organisms with a particular adaptation have a survival and reproductive advantage*. The frequency of correct statements went down from pre- to post-instruction answers for 13% of the students, although the decrease was not statistically significant ($p = 0.12$). In light of the fact that adaptation involves the differential survival and reproduction of organisms in a population, which causes increasing numbers of individuals in a population to inherit the advantageous trait (Gregory, 2009; Heddy & Sinatra, 2013), the decrease in frequency of students mentioning this correct idea is worrying.

Students’ perceptions of adaptation as a process and/or a product: It was not always easy to code answers, because while some students explicitly referred to process or product others did not, and this had to be inferred from the way they explained *adaptation*. For example, student GT08 specifically stated that adaptation was a process

> “Adaptation <u>is the process</u> by which living organisms features or characteristics change to fit their environment” (GT08)

while for students WSD12 and WSD14, understanding adaptation as a process had to be inferred:

> “the term adaptation <u>refers to the change in organisms</u> in order to suit a certain environment” (WSD12)
>
> “the ability of an organism <u>to develop</u> features to help with survival” (WSD14)

Before natural selection was taught in Grade 12 a little over a quarter of the students (28.9%) explained *adaptation* as both a product and a process. *Adaptation* was a topic they had previously encountered in earlier grades, but with a focus on product only. This fraction improved to a third of students after they learned about natural selection in Grade 12, even though adaptation *per se* was not specifically taught. An example of a student explaining *adaptation* as a product and a process in their answer is student WSD18:

> “The <u>process</u> by which <u>features</u> of an organism change as the environment changes” (WSD18)

About three-quarters of the students saw it only as a process (80% before and 73% after instruction). This is surprising in view of the fact that the focus in the Natural Sciences curriculum statements (RNCS and CAPS) is on adaptation as a product. About two-fifths of the group explained it only as a product (about 37% before and 43% after instruction on natural selection).

Specific correct statements in explanations of *natural selection*

Table 21 shows the statements included in students' answers, of the six scientific concepts that three experts had identified as important for a fully correct explanation of the term *natural selection.* They are ranked by frequency of students' correct statements.

Table 21: Frequencies of correct statements included in explanations of natural selection (n = 90)

Correct scientific ideas about natural selection	Pre-instruction	Post-instruction	Change	McNemar Chi^2
	Students including the concept			*p* =
1. Certain variations favour survival of the organism in its environment	8 (8.9%)	32 (35.6%)	26.7% ↑	0.0001*
2. Individuals in a population show variation (genetic and phenotypic)	1 (1.1%)	15 (16.6%)	15.% ↑	0.0005*
3. By surviving longer individuals with advantageous characteristics get to reproduce so have more offspring	1 (1.1%)	12 (13.3%)	12.2% ↑	0.002*
4. Individuals that lack the advantageous traits are less likely to survive and reproduce fewer offspring	1 (1.1%)	5 (5.5%)	4.4% ↑	0.1
5. The advantageous traits will thus be passed on to more offspring in the next generation than less advantageous features	1 (1.1%)	1 (1.1%)	0%	1.0
6. The proportion of advantageous traits increases in the population	1 (1.1%)	3 (3.3%)	2.2% ↑	0.32
Total	**13**	**68**		**0.009x10^8***
* statistically significant at *p* = 0.05 level				

The frequency of correct statements about natural selection improved for five of the six statements, but only three were statistically significant at the p ≥ 0.05 level: In section 4.1.1 (p. 69) I mentioned that the topic of *natural selection* had shown statistically significant improvement in the total number of correct statements from pre- to post-instruction.

The most common scientific idea in the pre-instruction instrument (that *certain variations favour the survival of an organism in the environment*) was also the most commonly mentioned in the post-instruction instrument and improved from one tenth of students citing it to a third of students (*p* = 0.0001). Two other ideas (that *individuals in a population show variation*, and the idea that *organisms with advantageous traits tend to survive and therefore reproduce more successfully*), showed improvements for 15% of the students (*p* = 0.0005) and 12% (*p* = 0.002) respectively. However, when looking at the individual concepts, it is apparent that only the first three of the six statements were mentioned significantly more often. Even though they improved significantly, the percent of students including them is still very low. Table 21 shows that all six statements of *natural selection* knowledge need to be dealt with more carefully by teachers, as very few students seem to be aware of these important points.

Concluding comments about students' explanations

Students' scientific explanations of *natural selection* after learning about *natural selection* were surprisingly weak across all three schools, considering that students had just been taught the topic. The most frequently included correct statement was included by only 36% of the students, followed by 17% for the next most frequently included. Important questions need to be asked about the presentation of the topic in South African classrooms. Are teachers teaching the key factors of natural selection in their lessons? Are textbooks presenting the six key concepts for natural selection in their explanations? Why are the key concepts necessary for a complete understanding of natural selection not explicitly stated in the curriculum documents? Should the topic be taught in earlier grades to provide students "with experiences that induce cognitive conflict […] and develop new knowledge" (Driver, Roselind; Asoko, Hilary; Leach, 1994, p. 6) and before students' misconceptions have become "entrenched" (Kelemen et al., 2014, p. 893)? Many researchers working in the field think so, e.g. Kelemen et al. (2014); Pobiner (2016); and Shtulman et al. (2016).

Specific correct statements in the scenario-based answers

The scenario-based questions in the pre- and post- diagnostic activities required students to apply their knowledge of *adaptation* and *natural selection* to four novel scenarios (two before instruction and two after instruction). Three experts had identified eight scientific ideas as being important for a complete and correct answer in each case.

Table 22 details the correct statements and their frequency in students' answers. Because the context of each question influences students' answers (see Engel Clough & Wood-Robinson, 1985a), the pre- and post-instruction instruments were designed with equivalent questions to keep the contexts as similar as possible, as outlined in Section 3.4.1 (starting on p. 47) in Chapter 3. In Table 22, I have clustered the equivalent questions together (i.e. the two insect questions and the two mammal questions) for ease of comparison.

A positive increasing trend can be seen for each of the key concepts in Table 22: All eight of the key concepts were mentioned more often after being taught about natural selection. This suggests that students' understanding of adaptation and their application of that understanding improves by learning about natural selection. It is important to keep in mind that no specific effort was made to link adaptation and natural selection during the teaching process.

Key concept 8 (*the proportion of the advantageous trait / allele in the population increases*), for the insect questions, was close to the traditionally accepted level of statistical significance ($p = \leq 0.05$) but did not quite reach it ($p = 0.06$), and was further away from statistical significance for the mammal questions ($p = 0{,}14$). Generally, very few students mentioned key concept 8 in their answers. This relates to key concept 2 (*the population shows variation of traits*), a concept that was almost entirely absent from students' answers before learning about natural selection. While statistically significant improvement was seen for key concept 2 after instruction about natural selection, for both the insect question and the mammal question, the proportion of students who saw the significance of *having variation in a population in order to adapt* remained low. Research suggests that students tend to view the locus of change to be within individual organisms rather than populations as a whole (Keskin & Kose, 2015; Yates & Marek, 2014). In the South African context, Moore et al. (2002) argue that "the problem seems to lie with […] the way metaphors of everyday knowledge inhibit the grasp of complex, abstract, and counterintuitive theories like evolution” (discussed further in Section 4.5, p. 108).

Three key concepts showed statistically significant improvements from pre- to post-instruction for both the insect and the mammal questions: Statistically significant improvements for key concepts 2, 4 and 6, for both the insect and mammal questions indicates that the students’ ideas were probably least affected by the context of the question for these three points than for the other five points.

Table 22: Frequencies of the eight correct ideas about adaptation, across the four scenario-based questions (n = 90)

	Insect questions				**Mammal questions**			
	***Peppered moth* (pre-teaching)**	***Fruit chafer beetle* (post-teaching)**	**% diff.**	**Paired t-test**	***Elephant* (pre-instruction)**	***Seal* (post-instruction)**	**% diff.**	**Paired t-test**
Total number of correct statements given by the group	110	203		$p = 0.3 \times 10^{-5}$*	51	173		$p = 0.2 \times 10^{-5}$*
Mean number of correct statements per student	1,22	2,26			0,57	1,9		
Key concepts of *adaptation*								
1. Only genetically inherited traits lead to adaptation	8 (8,9%)	11 (12,2%)	3.3% ↑	$p = 0{,}49$	5 (5,5%)	18 (20%)	14.5% ↑	$p = 0{,}004$*
2. The population shows variation of traits	2 (2.2%)	28 (31%)	28.8% ↑	$p = 0{,}2 \times 10^{-5}$*	1 (1,1%)	23 (25,6%)	24.5% ↑	$p = 0{,}3 \times 10^{-4}$*
3. Advantageous traits lead to increased survival	36 (40%)	43 (47,8%)	7.8% ↑	$p = 0{,}27$	11 (12,2%)	33 (36,7%)	24.5% ↑	$p = 0{,}9 \times 10^{-4}$*
4. Increased survival leads to more reproduction, so more offspring of that type	7 (7,8%)	21 (23,3%)	15.5% ↑	$p = 0{,}2 \times 10^{-5}$*	5 (5,5%)	28 (31,1%)	25.6% ↑	$p = 0{,}3 \times 10^{-4}$*
5. Lack of advantageous traits - less likely to survive	17 (18,9%)	32 (35,6%)	16.7% ↑	$p = 0{,}005$*	20 (22,2%)	24 (26,7%)	4.5% ↑	$p = 0{,}52$
6. Reduction of numbers of these organisms in the population	29 (32,2%)	43 (47,8%)	15.6% ↑	$p = 0{,}04$*	1 (1,1%)	24 (26,7%)	26.7% ↑	$p = 0{,}3 \times 10^{-5}$*
7. Over many generations	0 (0%)	4 (4,4%)	4.4% ↑	$p = 0{,}08$	3 (3,3%)	12 (13,3%)	10% ↑	$p = 0{,}02$*
8. Proportion of the advantageous trait / allele in the population increases	11 (12%)	20 (22%)	10% ↑	$p = 0{,}06$	5 (5,5%)	11 (12,2%)	6.7% ↑	$p = 0{,}14$

*significance level: $p = \leq 0.05$

Three key concepts showed statistically significant improvements for the mammal questions but not for the insect questions: Key concepts 1, 3 and 7 showed no statistically significant improvement in the insect questions, but improved significantly in students’ answers to the mammal questions. Ideas 1 and 3 were included by significantly more students (14.5% and 24.5% respectively).

An improvement of 10% was seen for key concept 7. The idea that *adaptation occurs over generations* (key concept 7) was low across all four questions, with 14% being the highest occurrence of the concept for any one question.

One key concept showed a statistically significant improvement for the insect questions and not for the mammal questions: Interestingly, only one key concept improved significantly between students' pre- and post-instruction answers to the insect question and not for the mammal question. Key concept 5 was more commonly mentioned in students' responses (35,6%) to the fruit chafer beetle question than any of the other three questions. This was a 16,7% improvement from students answers to the peppered moth question.

More statistically significant improvements were seen for the mammal questions than for the insect questions: Students' explanations in the pre-instruction elephant question contained very few correct ideas. More students gave 'off-track' answers to the elephant question because, for example, many (n = 24) thought that global warming was the reason why elephants ears 'had to' get bigger. The upper part of Table 22 shows that the number of correct ideas was substantially lower for the elephant question, a total of 51 correct ideas (of 720 possible correct ideas) were given, as compared to the total of 110 for the insect question. Again, context influences the sorts of answers students give in their explanations.

4.1.5 Concluding remarks for this section

Based on students' total scores, their ability to explain *adaptation* and *natural selection,* and to apply their knowledge in the scenario-based questions, improved after instruction on natural selection. However, students' inclusion of key concepts in their post-instruction explanations of *adaptation* remains low. Students' explanations of *natural selection* showed only small improvements and the mean number of answers per student in the explanation questions remained low. The teaching of natural selection improved students' understanding of adaptation and thus their general scientific literacy without any specific intervention. With this in mind, I would agree with those authors (e.g. Legare, Lane, & Evans, 2013; Shtulman et al., 2016) who argue for an age-appropriate inclusion of natural selection for students in younger grades.

4.2 ESSENTIAL CONCEPTS MISSING FROM STUDENTS' ANSWERS

This section answers the second research sub-question, shown below. There are presently no studies that I am aware of that have looked into what essential concepts necessary for a complete correct answer about evolutionary adaptation are missing from students' answers. Identification of the missing concepts will provide a number of educational stakeholders with useful information that could be used to improve teaching and learning.

Question b: What essential concepts are missing from students' explanations of biological *adaptation*, before and after learning about *natural selection*?

4.2.1 Concepts missing from students' explanations of '*adaptation'*

Table 23 shows the average performance for the whole group for the six key concepts of evolutionary adaptation that three experts felt were needed for a scientific understanding of the topic. The key concepts are arranged in order from the topic that was most included in students' answers to the most excluded concept.

Key concepts 4, 5 and 6 were missed by more than 90% of the group, both pre- and post-instruction: Only one student before instruction mentioned Key concept 4. The student said:

> "adaptation is plants or organisms change in order to successfully survive in their habitats due to natural selection eliminating those that are unable to survive and leaving those that are best suited to surviving" (PW22).

Natural selection is correctly identified by this student as the mechanism by which adaptation occurs. However, because no other student mentioned this idea in their answer, it is likely that student PW22 learned this concept outside of the classroom. Not one student mentioned key concepts 5 and 6 in their pre-instruction responses. Students were probably never taught these concepts. The curriculum document does not mention key concepts 4, 5, or 6 (see Section 1.3.1 and 1.3.2, p. 4 - 6), so it also does not get covered in textbooks. If students are to realise that adaptation is a process, and closely allied to natural selection, it needs to become a focus in the curriculum statements, otherwise it will not be included in textbooks and will not be taught.

Table 23: Frequencies of missing concepts for explanations about adaptation (n = 90)

	Percentage of students with correct and missing key concepts					t-test
	Pre-instruction		Post-instruction		Change	
	Included	Missing	Included	Missing		*p* =
1. Adaptation involves becoming more suited to the environment	67 (74.4%)	23 (25.6%)	54 (60%)	36 (40%)	**14.4% ↑**	0.23
2. Advantageous characteristics convey a survival and reproductive advantage on individuals with the trait	35 (38.9%)	55 (61.1%)	23 (25.6%)	67 (74.4%)	**13.3% ↑**	0.12
3. An adaptation can also be a specific advantageous characteristic (feature/ trait)	17 (18.9%)	73 (81.1%)	33 (36.7%)	57 (63.3%)	**17.8% ↓**	0.023*
4. Adaptation is a process that occurs by natural selection	1 (1.1%)	89 (98.9%)	3 (3.3%)	87 (96.7%)	**2.2% ↓**	0.32
5. Adaptation occurs in populations of organisms	0 (0%)	90 (100%)	8 (8.9%)	82 (91.1%)	**8.9% ↓**	0.005*
6. Adaptation takes many generations	0 (0%)	90 (100%)	6 (6.7%)	84 (93.3%)	**6.7% ↓**	0.014*

* statistically significant at p = 0.05 level

Four of the six key concepts were included in answers after instruction**:** Three of the statements were omitted significantly less often in the post-teaching answers. Statement 3 was missed by 17.8% fewer students (*p* = 0.02) and Statements 5 and 6 were omitted by 8.9% fewer students (*p* = 0.005) and 6.7% (*p* = 0.01) respectively, after instruction about natural selection. Teaching about natural selection seems to make more students aware of the importance of key concepts 3, 4, 5, and 6, although the two students who excluded Statement 4 in their post-instruction answers did yield a statistically significant difference (*p* = 0.32). This shows that even after instruction most students did not see the link between adaptation and natural selection. Whilst the frequency of missing statements decreased after instruction for topics 4, 5 and 6, more than 90% of the students were still missing these vital statements. Teachers need to be intentional about teaching these concepts in class (as recommended in Chapter 5).

Two key concepts (1 and 2) were missed by more students after instruction than before (although the changes were not statistically significant): Even after instruction, forty percent of students missed the crucial idea that *adaptation is about populations becoming more suited to the niche in which they live* (key concept 1). This is an increase of 14.4% in the number of students missing this idea from pre- to post-instruction. The crucial idea that *adaptations provide improved chances of survival and reproduction to those organisms that have them* was missing in 74% of students' answers after instruction, an increase of 13.3% omissions from pre- to post-instruction.

4.2.2 Concepts missing from the explanations of '*natural selection'*

The concept of natural selection is listed as a topic to be taught for the first time in Grade 12, yet nearly two-thirds of students in this study said that they had learned about it prior to Grade 12. So what did the students in this study know about natural selection before formal teaching on the topic in Grade 12? The omitted statements are summarized in Table 24.

Table 24: Frequencies of missing concepts in explanations of natural selection (n = 90)

Correct scientific ideas about natural selection	Percentage of students with correct and missing key concepts					t-test
	Pre-instruction		Post-instruction		Change	*p* =
	Included	Missing	Included	Missing		
1. Certain variations favour survival of organisms in their environment	8 (8.9%)	82 (91.1)%	32 (35.6%)	58 (64.4%)	26.7% ↓	0.0001*
2. Individuals in a population show variation (genetic and phenotypic)	1 (1.1%)	89 (98.9%)	15 (16.6%)	75 (83.4%)	15.5% ↓	0.0005*
3. By surviving longer individuals with advantageous characteristics get to reproduce, so tend to have more offspring	1 (1.1%)	89 (98.9%)	12 (13.3%)	78 (86.7%)	12.2% ↓	0.002*
4. Individuals that lack the advantageous traits are less likely to survive	1 (1.1%)	89 (98.9%)	5 (5.5%)	85 (94.5%)	4.4% ↓	0.1
5. The advantageous traits will thus be passed on to more offspring in the next generation than less advantageous features	1 (1.1%)	89 (98.9%)	1 (1.1%)	89 (98.9%)	0%	1.0
6. The proportion of advantageous traits increases in the population	1 (1.1%)	89 (98.9%)	3 (3.3%)	87 (96.7%)	2.2% ↓	0.32

* statistically significant at p = 0.05 level

Each of the six key concepts were missing in more than 90% of students' pre-instruction explanations: That *certain variations favour survival in an environment* was the only concept found in more than one student's answer (n = 8). The other five key concepts only had one mention among 90 students. Even the best student's answer excluded three correct ideas:

> "Natural selection is a theory proposed to explain the gradual change in a species. It proposes that if an organism benefits from a random genetic mutation that organism will be more likely to pass on its genes increasing the likelihood that the offspring will share the mutation and pass it on to its offspring" (WSV31).

Despite many of them saying that they had learnt about the topic in a previous grade, student WSV31 was the only student able to give three correct ideas about natural selection before learning about natural selection in class. Five of the six correct ideas were missing from 98,9% of students' answers.

There were post-instruction reductions in the number of missing concepts for five of the six ideas, three of which were statistically significant: More than a quarter of the students who missed key concept 1 before instruction included it afterwards, while key concepts 2 and 3 saw decreases of just over 10%. While each of these three concepts saw statistically significant decreases, they were still missing from the majority of students' explanations. Because variation is the raw material upon which natural selection operates to bring about adaptation in populations, it is important that educators note just how many students (83.4%) did not mention it in their explanation of natural selection even after having learnt about natural selection. Similarly, the notion of reproductive fitness is key to understanding natural selection, hence the need for the key concept "*organisms with the advantageous trait survive longer and, as a result, get to reproduce".* While the number of students missing this concept decreased by 12.2% (p = 0.02) post-instruction, more than 85% did not mention it in their post-instruction explanation of adaptation.

Despite formal teaching on the topic of natural selection, many students still omitted important concepts in their explanations of natural selection: More than 80% of students missed five of the six statements needed for a correct and complete scientific understanding of *natural selection*, even after instruction. About 95% of students missed three of the six core concepts after instruction. Only one student mentioned the fact that *advantageous characteristics are passed on to the next generation,* a vital concept to the whole process of adaptation in populations. Only three students mentioned the fact that *advantageous traits increase in proportion in the population over time,* which is the crux of natural selection. This supports the conclusion made by several authors (Bishop & Anderson, 1990; Gregory, 2009; Keskin & Kose, 2015) that natural selection is difficult for students to understand.

4.2.3 Concepts missing from students' responses to the scenario-based questions

The scenario-based questions went beyond the level of requiring students to just recall facts and explain their understanding of *adaptation* and *natural selection*; it asked them to apply their knowledge to unfamiliar situations. The scenario-based questions assessed students' scientific explanations of animal adaptations, and provided an opportunity to assess the degree to which students' ideas were consistent between the four scenarios.

Ideas missing from a student's responses could mean one of three things. Firstly, it could mean that a student does not have the requisite knowledge to answer the question. Secondly, it could mean that the student has an underlying alternative framework that inhibits the student from mentioning the key concept because they do not see it as relevant. Lastly, it could mean that the context of the question has influenced a student to answer in a particular way, as was found by Engel Clough and Wood-Robinson (1985a). In light of the last point, it is not always easy to interpret the results of the scenario-based questions, because the context of the question appeared to have affected students' answers. Of the eight key concepts students needed to include in their answers, two key concepts (3 and 6) had the largest percentage difference between the peppered-moth and elephant questions on the pre-instruction diagnostic activity and the fruit chafer beetle and seal questions on the post-instruction diagnostic activity. The issue of predation featured strongly in both the peppered moth and the fruit chafer beetle scenario-based questions and thus more students correctly included the idea that organisms with the advantageous trait were likely to survive longer. In the same way, the fruit chafer beetles that had the advantageous trait were less likely to succumb to predation and were also more likely to survive. The issue of predation did not feature at all in the elephant and seal questions and thus few students mentioned key concept 3 in their responses (see Table 25). Presumably, students reasoned that peppered moths and fruit chafer beetles with less advantageous traits would be less common in the population because they would be eaten by predators and thus more students included this idea in their response (key concept 6 in Table 25). Because the elephant and seal questions did not have a predator/prey relationship like the peppered moth and fruit chafer beetle questions, students were less inclined to include key concepts 3 and 6 in their responses to those two questions.

Table 25: Frequencies of missing concepts in the scenario-based questions (all percentages have been rounded to the nearest %)

	Percentage of students excluding statements						**Improved scores[†]**			
	Pre-instruction			**Post-instruction**			**Insect**	**t-test**	**Mammal**	**t-test**
Scientific statements necessary for correct answers	**Moth**	**Elephant**	**% diff**	**Beetle**	**Seal**	**%diff**	**%diff**	***p =***	**%diff**	***p =***
1. Only genetically inherited traits lead to adaptation +	91%	95%	4%	88%	80%	8%	3%↓	0.2	15% ↓	0.001*
2. Populations show variation of traits	98%	99%	1%	69%	74%	6%	29%↓	$0.7x10^{-7}$*	24% ↓	$0.3x10^{-6}$*
3. Advantageous traits lead to increased survival	60%	88%	28%	50%	63%	11%	10%↓	0.06	25% ↓	$0.5x10^{-4}$*
4. Increased survival increases the chances for reproduction, so more offspring of that type	92%	95%	3%	77%	69%	9%	15%↓	0.002*	26% ↓	$0.4x10^{-5}$*
5. Lack of advantageous traits among certain individuals in the population decreases their chances of survival	81%	78%	3%	64%	73%	9%	17%↓	0.001*	5% ↓	0.2
6. There is a reduction in the frequency of individuals with less advantageous traits in the population	68%	99%	31%	52%	73%	21%	16%↓	0.01*	26% ↓	$0.2x10^{-6}$*
7. Adaptation occurs over many generations	100%	97%	3%	96%	87%	9%	4%↓	0.02*	10% ↓	0.005*
8. Proportion of the advantageous trait / allele in the population increases	88%	95%	7%	77%	88%	10%	10%↓	0.02*	7% ↓	0.06

***** Statistically significant at the $p \leq 0.05$ level

+ epigenetics is not part of the school curriculum

† a reduction in missing answers constitutes an improvement

The other factor that potentially influenced the likelihood of students including key concepts 3 and 6 in their answers is the issue of urgency. Peppered moths and fruit chafer beetles were in immediate danger in those scenario questions, whereas the elephant and seals were not in immediate danger. Students were thus more likely to write about survival and death in the insect questions than they were in the mammal questions. Once again the context of the question appeared to have influenced the sorts of answers students provided. Further evidence that supports the notion that the context of the question influences students answers can be seen in the ‘improved scores column’ for key concept 3 in Table 25, which details improvement differences between the insect and mammal questions.

Trends in the data shown in Table 25

Key concept 2 saw the frequency of missing concepts decline the most, in both the mammal and the insect question from pre- to post-instruction: The 24% improvement ($p = 0.7 \times 10^{-7}$) before and after instruction between mammal questions and 29% ($p = 0.3 \times 10^{-6}$) improvement before and after instruction between insect questions proved to be statistically significant. That variation exists in populations is essential for the process of natural selection to take place to bring about adaptation and such an improvement suggests that some students have understood its significance and applied it to both scenario-based questions after instruction. The frequency of students missing key concept 2 after instruction in this study (+/- 70%) is similar to the frequencies that (Bishop & Anderson, 1990) found among 110 university students in the USA with varying years of prior biology education.

Key concept 7 was most frequently missed by students: Most students before instruction (100% insect, 97% mammal) and the majority of students after instruction (96% insect, 87% mammal) did not mention that adaptation takes generations to occur. This may be explained by the high number of students who mistakenly believe that adaptation occurs to individual organisms (see Section 4.3). While statistically significant improvements were found between pre- and post-instruction for both insect ($p = 0.02$) and mammal questions ($p = 0.005$), the concept is absent from most students’ answers. I found no data on the extent of students’ understanding of this key concept in the literature (see Section 2.3.5, p. 24).

Improved scores for key concepts 4 and 6 were almost identical: This may indicate a conceptual link between students’ understanding of *the benefit of improved survival and reproduction for organisms with advantageous traits* and a corresponding *decrease in the number of organisms without advantageous traits in the population* for the opposite reasons. After reviewing the data, however, it appears the similarities are coincidental. Many students mentioned key concept 4 and not key concept 6 and vice versa in all four questions.

While improvements were seen in the reduction of missing concepts, the frequency of missing concepts remains high: The frequency of students missing key concepts remains above two-thirds for six of the eight key concepts in Table 25. It is apparent that while Grade 12 students in this study learned about natural selection in Grade 12, their knowledge of the key concepts necessary to explain natural selection is weak. More attention needs to be paid to these topics when teaching natural selection.

4.2.4 Concluding remarks on missing concepts

After observing the high frequency of missing key concepts in students' answers to the scenario-based questions, a further question arises. Are the high frequencies of missing concepts evidence of a lack of content knowledge, or an inability to apply their knowledge to new and unseen scenarios? Bearing in mind that Bloom's taxonomy is a "cumulative hierarchy" where each level of cognitive demand subsumes all the demands from the cognitive levels below it (Amer, 2006; Krathwohl, 2002), there are two lines of evidence presented in this section that help answer this question. Firstly, many students are unable to apply their knowledge of *adaptation* and *natural selection* to the scenario-questions. Secondly, while students' understanding of natural selection and adaptation in this study varied, many fall on the weak end of the spectrum and struggle to meet the requirements of cognitive level 2 – comprehension (an ability to reorder, rethink and translate what they already know). This suggests that students are stumbling at level 1 of Bloom's taxonomy (knowledge). The majority of students are missing more than half the number of key concepts in their response to either the natural selection or adaptation explanation question, and missed at least half the correct answers to the scenario-based questions.

4.3 UNSCIENTIFIC IDEAS ABOUT ADAPTATION

This section answers research question c, restated below for convenience. It is important to keep in mind that I did not try and differentiate between acquired errors and true misconceptions. I have referred to all single scientifically incorrect ideas as 'misconceptions' in the layman's sense, as explained in Section 4.1 (p. 69).

Question c: What is the nature and extent of the students' unscientific ideas about biological *adaptation*, before and after learning about *natural selection*?

Table 26 shows the number of students, of the 90, that held certain misconceptions about the topic of *adaptation*, and illustrates the frequency of specific misconceptions for each question, for the pre- and post-instruction instruments. The misconceptions are ranked by the total pre-instruction frequency. When reading the table for this section, the colours in the body of the table should be ignored as they will form part of the discussion in a later section.

Students' unscientific ideas were assessed using the instrument described in Section 4.1 (p. 69).

4.3.1 Students' unscientific ideas about adaptation before instruction on natural selection

The first six misconceptions were frequently cited in students' explanations and the two scenario-based questions: The idea that *adaptation is caused by environmental changes* was the most commonly found misconception in the students' pre-instruction diagnostic activity (mentioned 169 times across the four questions). While this misconception was frequently mentioned in the **scenario-based questions** (72 students - 80% of the group, for the peppered moth; 62 students - 69% for the elephant), it was less frequently mentioned in students' **explanations** of *adaptation* and *natural selection*. With a total of 24 occurrences of this misconception in students' explanations of *adaptation*, it was the least frequently mentioned among the top six misconceptions for that particular question. In similar scenario-based questions, Cunningham and Wescott (2009) and Yates and Marek (2013) found similar levels of this misconception in undergraduate students (78%) and teachers (90%) respectively, suggesting that this is a common problem among students and teachers alike. This finding can also be scrutinised in terms of what South African students have been taught about adaptation in previous grades. The Grade 8 CAPS Natural Sciences document, which spells out what content needs to be taught, states the following: “adaptation allows the organism to survive as it adapts to changing conditions within the environment” (Department of Basic Education, 2011, p. 38). This statement suggests that adaptation has occurred because a change has occurred in their environment, and furthermore uses wording (‘the’ …. and ’it’) that clearly states that individual organisms adapt (the third most frequent unscientific idea, discussed later).

Table 26: Unscientific ideas in students’ written responses (n = 90)

	Pre-instruction total errors for group					Post-instruction total errors for group					
Specific unscientific ideas	Total	Adaptation	Natural selection	Peppered moth	Elephant	Total	Adaptation	Natural selection	Fruit chafer beetle	Seal	*p* =
1. Adaptation is caused by environmental changes	169	24 (27%)	11 (12%)	72 (80%)	62 (69%)	136 ↓	26 (29%)	7 (8%)	60 (67%)	43 (48%)	0.002*
2. Adaptations are needed in order to survive	152	62 (69%)	15 (17%)	38 (42%)	37 (41%)	132 ↓	51 (57%)	11 (12%)	34 (38%)	36 (40%)	0.049*
3. Individual organisms adapt	100	59 (66%)	6 (7%)	25 (28%)	10 (11%)	79 ↓	40 (44%)	13 (14%)	12 (13%)	14 (16%)	0.025*
4. Organisms adapt in their life time	99	58 (64%)	8 (9%)	24 (27%)	9 (10%)	88 ↓	41 (46%)	12 (13%)	21 (23%)	14 (16%)	0.16
5. Organisms are aware of the need to change	84	43 (48%)	8 (9%)	19 (21%)	14 (16%)	61↓	27 (30%)	6 (7%)	16 (18%)	12 (13%)	0.012*
6. The organisms initiate the changes	59	41 (46%)	7 (8%)	7 (8%)	4 (4%)	52↓	29 (32%)	5 (6%)	9 (10%)	9 (10%)	0.23
7. Those with less advantageous traits die / become extinct	32	2 (2%)	21 (23%)	4 (4%)	5 (6%)	63 ↑	3 (3%)	33 (37%)	9 (10%)	18 (20%)	0.000004*
8. Individuals with advantageous traits WILL survive	24	1 (1%)	21 (23%)	0 (0%)	2 (2%)	41↑	5 (6%)	35 (39%)	1 (1%)	0 (0%)	0.002*
9. Only the strongest survive	18	0 (0%)	18 (20%)	0 (0%)	0 (0%)	19↑	0 (0%)	15 (17%)	4 (4%)	0 (0%)	0.42
10. Advantageous traits WILL pass to ALL offspring	14	1 (1%)	5 (6%)	5 (6%)	3 (3%)	22↑	1 (1%)	14 (16%)	1 (1%)	6 (7%)	0.09
11. Eventually all individuals in a population will have the advantageous trait	10	0 (0%)	5 (6%)	3 (3%)	2 (2%)	17↑	1 (1%)	3 (3%)	8 (9%)	5 (6%)	0.072
12. Those with advantageous traits WILL reproduce	7	0 (0%)	5 (6%)	2 (2%)	0 (0%)	7	1 (1%)	5 (6%)	1 (1%)	0 (0%)	0.5
13. Only individuals with advantageous traits interbreed	3	0	2	1	0	6↑	0	6	0	0	0.15

*= statistically significant at the p ≤ 0.05 level

🟨 ‘Evolution on demand’ misconceptions 🟧 ‘Survival of the fittest ‘ misconceptions

A number of students who mentioned that the environment causes adaptation used wording similar to that of the curriculum document.

> "The moth needed to evolve in order to keep its camouflage. Since it was getting darker with the soot around England the moth started to pick up the trait of being darker in order to continue to blend with their surroundings." (PW37).

A second student, in response to the elephant scenario-based question, said:

> "Elephants had smaller ears in the past. Because, like other animals, elephants have started to change shape. The environment (earth) started to change and cause animals to change and their features to change. (WSV25)

The second most common pre-instruction misconception was the idea that organisms *adapt* because *they need to in order to survive*. The frequency of this misconception in the students' **explanation** of *adaptation* (69%) was approximately double that in their responses to the **scenario-based questions** (42% and 41%). This suggests that many students intuitively link the process of *adaptation* with an organism's need to adapt, a teleological idea discussed further in Section 4.5.1 (p. 108). The idea that organisms *adapt* in order to survive was the most common unscientific idea in many studies reported in the literature, with 13 of the 22 papers I reviewed identifying it as a problem. Two examples of this unscientific idea in students' answers are provided below. The first is inferred from a student's **explanation** of *adaptation*.

> "Adaptation is when organisms or animals have to adapt to their habitat in order to survive. They adapt so that they can be better with what they do to survive…" (GT10)

The second is inferred from a student's response to the elephant **scenario-based question**:

> "Elephants probably lived in an area which was not hot and sunny and so had no need for temperature regulation, however as conditions changed over the years elephants needed to adapt in order to survive" (WSV 19)

The third most frequent pre-instruction misconception in this study was the idea that *individual organisms adapt*. The most frequent mention of this misconception was in students' **explanations** of *adaptation* (66% of the students). The unscientific idea that individual organisms adapt is commonly reported in the literature. Brumby (1984), for example, found that 60% of first-year medical students at one Australian university stated that individual organisms adapt. This misconception seems to be closely associated with the fourth most common unscientific idea, often implied rather than explicitly stated, that *organisms adapt in their lifetime,* appearing in 64% of the students' answers. But, as shown in the two examples below, if the organism in question is referred to in the singular, those changes would have to happen during that organism's lifetime.

> "Adaptation is an organisms ability to change in order to survive according to the season, weather location" (GT14).
>
> "It is the ability of something to change in order to meet its need at the given time, to change so it can survive" (WSV2).

The misconception that *organisms are aware of the need to change* was the fifth most commonly mentioned or implied by the students in this study (84 times across the four questions on the pre-instruction diagnostic activity), almost half of them being mentioned in students' **explanations** of *adaptation,* for example:

> "adaptation is to change physical qualities in an organism in order to be able to survive conditions that it is facing" (PW37)

The underlined section in this response implies that the organism is aware of the conditions around it. The following answer (from a scenario-based question) states it more explicitly.

> "The grey moths do notice a change in colour with the tree trunks and they soon realise that they are not camouflaging any so now they need to adapt to the same colour of the tree trunk. In order to camouflage once again" (GT09)

The idea that organisms are aware of a problem is often associated with the sixth most common misconception, that *organisms initiate the change.* For example:

> "Adaptation means that an organism finds a way to better suit itself to its environment when changes occur. It has to change specific things about itself around it to make sure the environment is a suitable and more habitable place for it to live" (PW31).

This student's response illustrates the link between students thinking that organisms are aware of their need to change and the idea that organisms actually initiate the change. Two further examples of this sixth most common misconception are:

> "Adaptation refers to how an organism is able to change itself in order to survive in an area" (PW30)

> "Adaptation is when plants or animals etc. change and adapt to match its surroundings in order to survive. Done voluntarily. Surrounding could have been changed by man made structures or products" (GT11).

This misconception is also commonly reported in the literature. Keskin and Kose (2015) found that 67% of 117 pre-service teachers at a university in Turkey held this misconception and Tamir and Zohar (1991) reported that 81% of 16 Year 10 students at a school in Israel also held this unscientific idea.

These six most-frequently occurring misconceptions are associated with an 'evolution on demand' alternative framework, discussed further in Section 4.4.

The last seven misconceptions (less frequently mentioned) were more frequent in students' explanations of natural selection, than adaptation: The unscientific idea that *those organisms in a population that have less advantageous traits WILL* (emphasis added*) die or go extinct* was the seventh most common misconception (32 occurrences across all four questions on the pre-instruction diagnostic activity) and the joint most common (21 occurrences – 23%) in students' **explanations** of *natural selection* (see Table 26). In the literature, it was held by 64% of undergraduate students at a university in the United States (Cunningham & Wescott, 2009) and by 63% of 536 high school students in 32 public high schools in Oklahoma, United States (Yates & Marek, 2014). The unscientific idea *that individuals with advantageous traits WILL survive* was the eighth most common unscientific idea (24 occurrences) in students' answers to the pre-instruction instrument across all four questions, and joint most common in their explanations of *natural selection* (21 occurrences, 23%) with the idea that *organisms with less advantageous traits WILL die.* These two unscientific ideas were commonly mentioned together in students' explanations of *natural selection*. For example,

> "Natural selection is the process where those that are unable to survive are eliminated which allows for those most suited to surviving to survive" (PW22)

Another student included in her answer the two misconceptions mentioned above as well as the tenth most common misconception (14 occurrences across the four pre-instruction questions) that *advantageous traits WILL be passed on to the next generation.*

> "Natrual (sic) selection is when organsims evovle (sic) in order to adapt to their environment or other factors so that they survive. Those that do not evovle (sic) or adapt die out while the organisms that have adapted survive and pass on the adaptation to their offspring" (GT14)

The ninth most common unscientific idea was the idea that *only the strongest survive* and was mentioned on 18 occasions and only in students' explanations of *natural selection*. This unscientific idea was also commonly mentioned alongside the idea that organisms with less advantageous traits will die.

> "Natural selection is a process whereby the strong live on and the weak die. The theory is that nature will naturally select who it wants to live on i.e. the strong and also who it wants to die i.e. the weak" (WSV10)

> "It is like survival of the fittest. In nature the stronger specimen survives while the weaker will die out. It is natures way of making sure the stronger most fit specimen survives" (WSV11).

4.3.2 Students' unscientific ideas about adaptation after instruction on natural selection

All of the top six misconceptions showed decreased frequencies after instruction on natural selection: There was a decrease in the frequency of the first six misconceptions identified in Table 26, four of which were statistically significant at the traditional $p \leq 0.05$ level of statistical significance used in education research (Fraenkel et al., 2012). The level of significance, also called a confidence interval, indicates the probability that a result occurred by chance (Samuels & Witmer, 1999). Probabilities above the $p = 0.05$ level indicate a higher likelihood that the result occurred by chance. Those below $p = 0.05$ indicate a lower likelihood that the result occurred by chance (Norman, 2010).

The misconception that the *environmental change causes adaptation* saw a significant decrease ($p = 0.002$) in frequency from pre-instruction answers (169 occurrences across all four questions) to post-instruction (136 occurrences in all four questions), more so in the **scenario-based questions**. Students' erroneous ideas about the role of the environment in adaptation may stem from unscientific statements in the Natural Sciences (RNCS) or the Life Sciences (CAPS) curriculum documents, or from textbooks based on the these curriculum statements. The sample for this study was composed of two student cohorts and each cohort was exposed to the RNCS for varying lengths of time (see section 1.3.1, p. 4). In this time they may have been exposed to textbooks with the erroneous idea that the *environment causes organisms to adapt*. Sanders and Makotsa (2016) found three South African Natural Sciences textbooks that contained this error. In the Grade 12 Life Sciences CAPS document, the detail on natural selection ambiguously states "Evolution (change) through natural selection (link to genetics): depends on […] changes in the environment" (Department of Basic Education, 2011b, p. 61). Textbooks and teachers may communicate similar unscientific or ambiguously worded ideas to the students.

The second misconception with a statistically significant decrease in frequency was the idea that *organisms are aware of their need to change (p* = 0.012). While this anthropomorphic idea does not occur in the curriculum statements or textbooks, it may be caused by the anthropomorphic explanatory language used by teachers, parents, or certain sources in the media (Horowitz & Bekoff, 2007; Legare et al., 2013). While most students who mentioned this unscientific idea in their pre-instruction instrument just left it out of their post-instruction answer, one student was clearly aware that adaptation was not a conscious process.

> "…when a population of organisms unconsciously change their behaviour or biological morphology to better suit their environment" (WSD10)

What prompted the student to make this statement is unknown. However, the fact that the student mentioned it suggests he had thought about it.

Other misconceptions that saw statistically significant decreases in frequency after instruction include the idea that *individual organisms adapt* (*p* = 0.025), and that *organisms change in order to survive* (*p* = 0.049). These decreases occurred in spite of the frequent mention of these two misconceptions in Natural Sciences (Sanders & Makotsa, 2016) and Life Sciences (Tshuma & Sanders, 2015) textbooks in South Africa, so could possibly be attributed to correct teaching of natural selection.

The unscientific ideas that *organisms adapt in their lifetime* and that *organisms initiate the change* also decreased in frequency after instruction but as the *p*-values were above the *p* = 0.05 level, they could just have occurred by chance. Other studies also found these two misconceptions to be common among students in various countries (e.g. Jungwirth, 1975; Keskin & Kose, 2015; Tamir & Zohar, 1991), highlighting just how pervasive and problematic these misconceptions are. The data suggests that the unscientific ideas that *organisms adapt in their lifetime* and that *organisms initiate the change* misconceptions are more resistant to change and may require teachers to address them directly in class, as advised by Bishop and Anderson (1990). My impression is that the erroneous idea that *organisms adapt in their lifetime* comes from the phrases found in the CAPS Natural Sciences Grade 8 curriculum, like, "adaptation allows <u>the organism</u> to survive as <u>it</u> adapts to changing conditions within the environment" (Department of Basic Education, 2011a, p. 38). The idea that *organisms initiate the change* may stem from references to an organism's ability or lack of ability to change if a change occurs in the environment. An example is found in the CAPS Natural Sciences Grade 8 curriculum statement, "organisms that are <u>unable to adapt</u> to changes within the environment <u>die out</u> (<u>become extinct</u>)" (Department of Basic Education, 2011a, p. 38).

Worryingly, increases in total frequency of mention of six of the thirteen misconceptions (numbers 7-11, and 13 in Table 26) were recorded from pre- to post-instruction, two of the six total increases being statistically significant. These were the idea that *organisms with less advantageous traits die or become extinct* (*p* = 0.000004) and the idea that *individual organisms with advantageous traits will survive* (*p* = 0.002). An increase in this misconception was particularly high in students' explanations of *natural selection.* Below is an example of a student who did not mention this misconception in their pre-instruction explanation of *natural selection*, but then mentioned it after instruction:

Before instruction:

> "Natural selection is when plants and animals selection (sic) what they need in order to survive and it is within their nature to choose it" (GT09)

After instruction:

> "It is survival of the fittest. <u>The strongest animals or species will survive</u> and <u>the weakest will die out</u>. They almost have to fight to survive. It is the animal or species that is most suited for the environment" (GT09).

The phrase 'survival of the fittest' is often used as a synonym for *natural selection* (Gregory, 2009; van Dijk & Reydon, 2010). This has led to many misconceptions about the process of *natural selection* because students misunderstand the meaning of the word 'fit'. Instead of using it to refer to an organisms improved chance of survival and reproduction, students tend to view it as a synonym for strength (Gregory, 2009; Sanders, 2014a). Another problem is the increase of 41 students (n = 24) who included after instruction that *all organisms with an adaptation will survive* (*p* = 0.002). It is important that students are taught that some, if not many, will die from disease or are eaten by predators, even if they have traits that favour survival. Some students maintained in both pre- and post-instruction explanations of *natural selection* that the strong will survive and the weak will die, as shown in the following example.

Before instruction:

> Natural selection is when organisms evolve in order to adapt to their environment or other factors so that they survive. Those that do not evolve or adapt die out while the organisms that have adapted survive and pass on the adaptation to their offspring (GT14).

After instruction:

> Natural selection is where organisms in a population who are fittest for their environment survive. Whilst those who have not adapted die out or reproduce at a lower rate and eventually become extinct (GT14).

4.3.3 Unexpected ideas in students' responses to the questions in the diagnostic activity

Some students gave unusual and unexpected answers about *adaptation*. While these strange ideas were generally in the minority, it serves to highlight the fact that some students do have unexpected unscientific ideas and it is "important to know the range of ideas that students may bring to their studies of evolution" (Engel Clough & Wood-Robinson, 1985a, p. 41). This section details some of unusual ideas that emerged in the answers to the questions in the diagnostic activities, both before and after the students learned about *natural selection* in their Grade 12 year.

Unexpected answers in students' explanations of *natural selection*

Two students suggested that *natural selection* involves the sacrifice of some organisms in the population so that other organisms in the population can live. The first student mentioned it in their post-instruction response.

> "The weak are eliminated so the best suited organisms survive" (WSV13)

The second student stated it more explicitly, and in both the pre- and post-instruction answers.

Before instruction:

> "The selection of certain individuals that are chosen to die in order to save the population" (PM43)

After instruction:

> "The weak, injured or sick are killed off in order to ensure a strong and healthy population" (PM43)

Three students thought that an organism deliberately chooses its mate based on certain qualities. One student communicated this in both her pre- and post-instruction responses.

Before instruction:

> "Animals will have a choice when they have to mate. The strong will mate with the strong in order to give their young a better chance at survival and to produce strong offspring" (WSV28).

After instruction:

> "Natural selection is the process by which a mate is chosen on the basis of their ability or adaptations to survive. The strongest organism within the species mate to give their offspring a better chance of survival" (WSV28).

Another student had this idea only in his post-instruction answer.

> "The selection of a mate with the intension (sic) of reproduction and carrying on their species. The selection of mates is to select the strongest gene ie best looking in order to achieve optimum survival" (PD03)

A third student explained a similar idea but emphasised that this occurred naturally, without human involvement.

> "No humans are involved in the reproduction strategies or in the mating strategies of other organisms and those organisms freely pick or choose related to who they want to mate with without any unnatural interference it happens as it is supposed to. The offspring do not have to have the selected genes that are wanted but have any genes from the randomly mated parent – naturally" (PW31).

Unexpected unscientific answers that emerged in students' responses to the insect scenarios

Some students said that the colour change in the peppered moth and the fruit chafer beetle were caused by environmental factors. Common environmental causes that students cited for the colour change in the peppered moth population were the pigments on the bark, or soot that the moths absorbed into their bodies, consumed, or inhaled. Common environmental causes cited in students' answers for the colour change in the fruit chafer population were the pigment in the acacia trees and in the beetles' diet, which the beetles either landed on or ate.

In response to the peppered moth question, 12 of the students (13% of the sample) said that soot (from the pollution) was deposited on the wings of the moth, making the moth darker.

> "Thus due to constant soot and ashes which fell upon their wings was therefore perhaps absorbed in their wings and caused the colour of their wings to change in colour thus causing darker moths to appear and the original grey pepper moths to become extinct" (GT05)
>
> "…They gathered soot on themselves and then turned dark" (WSV04).
>
> "The smoke and soot would sink into the feathers and skin of the moth causing an effect on the colour…" (PD01)

Fewer students (three students in the post-instruction instrument) communicated a similar misconception, that the beetle absorbs the green pigment from the tree.

> "This might have happened due to the pigment in the leafy acacia trees that caused the beetles exterior to change from a generally yellow colour to a more emerald through a chemical reaction" (GT01)
>
> "The chlorophyll, green pigment in plants was absorbed so there was a beetle with a genetic trait that was more green and this beetle reproduces, the greener beetles survived better as they could camouflage with the plant" (PW36)

Two students said that a colour change occurs in a moth when the bark of the tree is consumed:

> "…the moths would be exposed to that new colour of the bark as moths eat/consume the tree bark and therefore become any colour the bark is, therefore camouflaged" (WSV03)
>
> "The moths could have been feeding off the grey bark and this grey substance that accumulates from the bark and affects their colour and overall appearance" (WSD05)

Four students on the post-instruction instrument said that the beetles' colour changes because of their diet.

> "…and that food source from the acacia trees may have gradually changed their pigment to an emerald green over generations until they were completely that pigment that they were to camouflage amongst green plants" (GT05)

Considering that these students had learnt about genetics, specifically inheritance and variation, prior to their study of evolution by natural selection, it is alarming that these few students had such illogical ideas. Perhaps these students have not thought about these issues prior to formal learning in the classroom and are thus providing spontaneous answers for the sake of amusement, something Piaget (cited by Posner & Gertzog, 1982, p. 192) called "romancing" (see Table 27). A number of the answers provided by students showed evidence of the problematic response types identified by Piaget.

The categories of response that Piaget (1929) identified help researchers sift between what students actually think or believe, and what students want researchers to think they believe. In other words, there is a difference between answers that reveal a student's' thoughtful and internally constructed ideas and those that a student gives to deflect attention away from the fact they do not know, or what they actually believe. While this system was designed to categorise students' answers to clinical interviews and not written answers, it is still applicable to the diagnostic activity in this study because the diagnostic activity can be considered as a form of 'written interview', the only limitation being an inability to probe students' responses. Ultimately, I am looking for answers that reveal a student's beliefs and ideas about adaptation, something Piaget called "liberated and spontaneous convictions that most directly uncover the nature of children's logic and beliefs" (Posner & Gertzog, 1982, p. 129). Sometimes, though, students provide random answers or romanced answers which are evidence of little thoughtful consideration of the topic. Piaget's categories of response and some examples from students answers to the pre- and post-diagnostic activity are given in Table 27. These illustrate some of the potential difficulties researchers have in making valid interpretations of their data.

Table 27: Categories of responses to clinical interviews as defined by Piaget (1929, cited by Posner & Gertzog, 1982)

Type of response	Example from responses in this study
Answers at random: The student does not know the answer and makes up an explanation on the spot. Provides the first answer that pops into their head. (S)he might appear uninterested.	"…the moths would be exposed to that new colour of the bark as moths eat/consume the tree bark and therefore become any colour the bark is, therefore camouflaged" (WSV03)
Romancing: A story invented at the time in an effort to please the interviewer, although the student doesn't believe it.	"The tree barks got suffocated as there was not enough CO2 to keep them healthy and in their normal state. Because the bark became darker, the moths also did as a result of adaptation and survival (in order for them to still be well camouflaged). The moths could have been feeding off the grey bark and this grey substance that accumulates from the bark and affects their colour and overall appearance" (WSV22)
Suggested conviction: An answer that a student gives based on what the interviewer has said. It can be stimulated by the interviewer's line of questioning.	No examples were found.
Liberated conviction: The result of original thinking on the part of the student during the interview.	"The smoke and soot would sink into the feathers and skin of the moth causing an effect on the colour. Over the years the genes started to change and added the darker colour skin and feathers to the gene's creating a darker moth naturally" (PD01)
Spontaneous conviction: The student has thought about the concept previously, and provides an answer they believe to be correct.	"There was a large number of seals. There was variation in the population where some had the genes that allowed them to stay under water for long and some didn't. There was competition for food. The seals that could stay under water for long were able to hunt for fish deep under the sea and so they survived and may reproduce. The seals that can only stay under water for short periods of time were not able to get food and therefore, die. Number of seals that could stay under water for long increased. Population evolved" (PW23).

Unexpected unscientific ideas emerging in answers to the mammal scenarios

In response to the elephant question, some students saw the cause of the adaptation as something the elephant did, like moving to a new environment (n = 5). For example:

> "The elephants predecessors migrated to hot regions of the world. The smaller ears they had would grow to adapt to the new environment…" (WSV14)
>
> "As time passed and elephants emerged/ migrated in Africa the climate was much hotter therefore they needed a way to regulate their body temperature. They then adapted their ears to grow larger and larger so they could live in the hot climate" (WSV10)

Others saw the change in ear size being due to the Lamarckian notion of ears growing bigger because the elephants used their ears more (n = 8), for example:

> "Elephants use their ears to cool themselves down so adapting to climate change where it gets hotter would mean that they use their ears more which is why they probably got bigger" (GT11)
>
> "When elephants had small ears they would flap their ears to cool themselves down. Over the years their ears started to stretch and get bigger because of all the flapping that had occured over the years". (PD01)
>
> "Therefore in order to preserve the life of elephants in hotter climates their ears gradually grew to work as fans which improved their ability to cope in hotter climates which they need in order to survive" (PM52)
>
> "Elephants develop larger ears due to evolution and changes in the climate which required elephants to fan themselves with their ears to keep cool in the hot dry weather that occurs" (PW29)

The last two ideas, mentioned above, are consistent with a Lamarckian framework (discussed in Section 2.4.2, p. 35). It is important to keep in mind that these answers were given before students learned about natural selection. One student, who used the Lamarckian framework in her response, wrote:

> "Gradually as the earth began to heat and the elephants were moved to a hotter climate their ears would have evolved to get bigger in order to fan the elephants body and act as a sun barrier for its body so that the elephant does not over heat" (PW28)

In response to the seal question, the only strange answer found (9 students - 10% of the sample) was the idea that seals are capable of breathing underwater, for example with gills. Such an idea shows a lack of general biology knowledge. Two examples are:

> "The changed happened through evolution because as times change, the seals adapt and develop their ability to breathe under water" (GT06).
>
> "Ancient seals couldn't hold their breath. As years passed water density increased therefore more seals had to adapt. The weak links died (survival of the fittest). Gills evolved and adapted" (PM49).

Seven students (8% of the group) showed Lamarckian ideas similar to those found in the elephant question. In this particular example, students said that the seals developed better lungs as they spent more time under water.

> "The modern seals have adapted to their environment they have forced themselves to stay under water so that they could adapt to stay under water longer, causing a change by practice" (WSV25)
>
> "Mainly of deeper parts of the sea, in order to survive the newer seals developed larger lung capacity in order to catch fish by staying under water for longer" (PD20).

4.3.4 Summary of students' incorrect ideas included in their answers

The previous section dealt with the sorts of misconceptions students provided in their answers before and after instruction. This section shows the subtle differences of the groups' performance by presenting the number of misconceptions as distribution categories. Post-instruction changes are revealed most clearly when the data is shown graphically (see Figure 11), whilst Table 27 (following the graphs) provides more detailed information.

There appears to be an association between the teaching and learning of *natural selection* and an overall reduction in students' unscientific ideas about *adaptation*, particularly in students' **explanations** of *adaptation* (see Figure 11). The trend lines in the following graphs serve to highlight the shift in categories of students' responses from pre-instruction (dotted line) to post-instruction (solid line) responses. The position of the trend lines shifts to the left in the adaptation graph, indicating a decrease in the frequency of incorrect ideas in students' responses to the adaptation explanation questions from pre- to post-instruction.

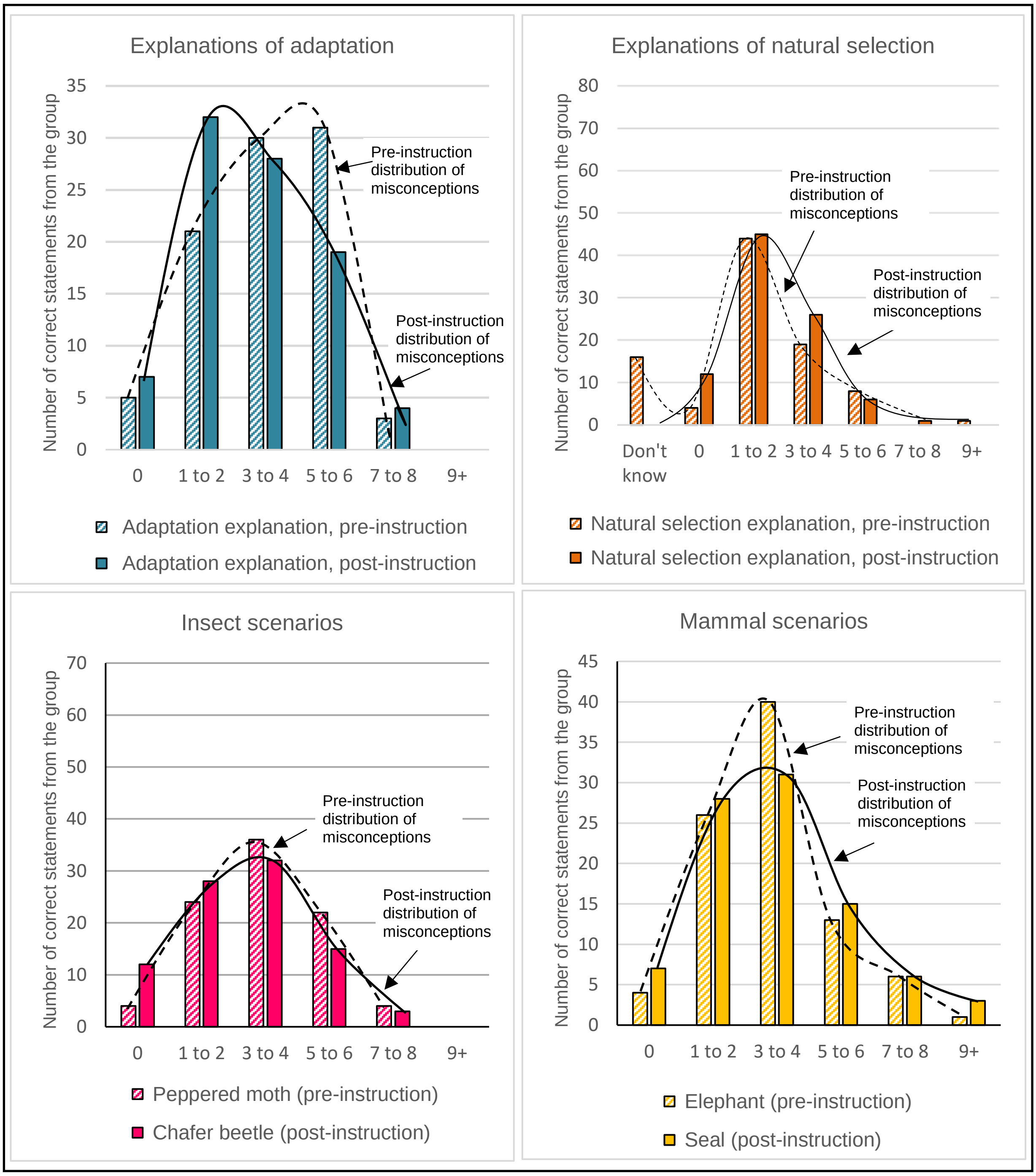


Figure 11: Number of misconceptions in students' answers, by category

The opposite is true for the number of incorrect ideas in students' responses to the *natural selection* explanation question. Students were more likely to provide incorrect ideas in their explanation of natural selection after instruction than before instruction (see the graph illustrating mark distributions for *natural selection*). There is a definite shift in the position of the post-instruction trend line to the right, indicating an increase in the number of unscientific ideas, with more students with a higher number of misconceptions. This finding is similar to that made by Yates and Marek (2014) who found that though students were more confident in their ability to explain natural selection, this did not lead to a corresponding decrease in the number of misconceptions in students' answers, and that in some cases misconceptions were more frequent.

There is little to distinguish between trend lines for the **scenario-based questions**. The position of the post-instruction trend line on the insect scenario graph nearly matches that of the pre-instruction trend line. However, the height of the bars indicates decreases in the number of post-instruction incorrect ideas in the higher mark categories and corresponding increases in lower mark categories. A slight shift to the right in the *mammal* **scenario-based** trend lines indicates increases in the number of incorrect ideas in the higher categories.

The data from which the graphs in Figure 11 were drawn is shown in Table 28. The number of students (shown in column three) in each misconception frequency category (see column two) is shown by question (column one) for both pre- and post-instruction. It is important to keep in mind when looking at the data in Table 28 that more students in the lower categories, and fewer students in the higher categories indicates progress in understanding.

More students had only zero, one or two misconceptions in their **explanations** of *adaptation* after instruction (29% of the group before instruction, up to 44% afterwards). Fewer students had five or six misconceptions after instruction (a drop of 13%, from 34% of the group before instruction to only 21% of the group afterwards). The overall reduction in the frequency of misconceptions in students' explanations of *adaptation* suggests that there is a positive relationship between the teaching of natural selection and the reduction of misconceptions about adaptation.

Fewer students (16% of the group) did not answer *the natural selection* **explanation** question after they had learned about natural selection, which suggests that students were confident enough to try and explain the concept. There was a 9% increase in the number of students in the desirable category of 'zero' misconceptions which means that the number of students with no misconceptions in their explanations improved. The 8% increase in students with between three and four misconceptions is worrying, although the change in this figure may be the result of the higher number of students answering the question.

There were 9% more students in the desirable '0' misconceptions category for the post-instruction *insect* **scenario-based** answers and 4% more for the *mammal* post-instruction answers. Notable decreases in the frequency of misconceptions were seen in high 5-6 misconceptions category (from 24% of the group before instruction, down to 17% after instruction) in the *insect* scenario answers, and the category with 3-4 misconceptions (10% decrease from 44% before, to 34% after instruction) for the *mammal* answers. On the whole though, low single figure increases or decreases in the number of misconceptions in the scenario-based questions suggests that the teaching of natural selection does not lead to noticeable reductions in the number of misconceptions that students have about adaptation. Perhaps a more definitive link between adaptation and natural selection while the topic of natural selection is being taught would reduce the frequency of incorrect ideas. This is a possible area of further research.

Table 28: Number of misconceptions in students answers, by category (n = 90)

Pre-instruction			Post-instruction			
Question	**No. of misconceptions**	**No. of students**	**Question**	**No. of misconceptions**	**No. of students**	**% of group**
Explanation of terms (comprehension level questions)						
adaptation	0	5 (6%)	adaptation	0	7 (8 %)	2%↑
	1-2	21 (23%)		1-2	32 (36%)	13%↑
	3-4	30 (33%)		3-4	28 (31%)	2%↓
	5-6	31 (34%)		5-6	19 (21%)	13%↓
	7-8	3 (3%)		7-8	4 (4%)	1%↑
	9+	0 (0%)		9+	0 (0%)	0%
natural selection	Do not know or no answer	14 (16%)	natural selection	Did not answer the question	0 (0%)	16%↓
	0	4 (4%)		0	12 (13%)	9%↑
	1-2	44 (49%)		1-2	45 (50%)	1%↑
	3-4	19 (21%)		3-4	26 (29%)	7%↑
	5-6	8 (9%)		5-6	6 (7%)	2%↓
	7-8	0 (0%)		7-8	1 (1%)	1%↑
	9+	1 (1%)		9+	0 (0%)	1%↓
Scenario-based questions (application level questions)						
peppered moths	0	4 (4%)	fruit chafer beetles	0	12 (13%)	9%↑
	1-2	24 (27%)		1-2	28 (31%)	4%↑
	3-4	36 (40%)		3-4	32 (36%)	4%↓
	5-6	22 (24%)		5-6	15 (17%)	7%↓
	7-8	4 (4%)		7-8	3 (3%)	1%↓
	9+	0 (0%)		9+	0 (0%)	0%
elephants	0	4 (4%)	seals	0	7 (8%)	4%↑
	1-2	26 (29%)		1-2	28 (31%)	2%↑
	3-4	40 (44%)		3-4	31 (34%)	10%↓
	5-6	13 (14%)		5-6	15 (17%)	3%↑
	7-8	6 (7%)		7-8	6 (7%)	0%
	9+	1 (1%)		9+	3 (3%)	2%↑

4.4 STUDENTS' USE OF VARIOUS ALTERNATIVE FRAMEWORKS

This section answers research question d. Table 26 in section 4.3, on page 90 is used when answering this research question as it lists, from most common to least common, the misconceptions that students in this study had about adaptation. Interestingly, the six most common misconceptions in the pre-instruction diagnostic activity were all part of the ‘evolution on demand’ alternative framework (see Table 26), while the last six misconceptions, occurring less frequently, were a part of the ‘survival of the fittest’ alternative framework.

Question d: To what extent do students exhibit alternative frameworks when explaining adaptation?

Sanders (2014b) describes ‘evolution on demand’ as an alternative framework incorporating a set of interconnected ideas through which some students understand biological change in organisms.

4.4.1 Students’ use of the ‘evolution on demand’ alternative framework

The phrase ‘evolution on demand’ was used by Jensen and Finley (1995) to describe the scientifically incorrect ideas that adaptations develop as a result of an organism’s desire for a particular trait, or because the organism needs it, usually in order to survive. The ‘evolution on demand’ alternative framework is a particular obstacle to understanding adaptation, for reasons associated with, but not limited to, the everyday meaning and usage of the word ‘adaptation’, the multiple meanings of the word ‘adaptation’ in science, and the tendency for students to use anthropomorphic and teleological language in their explanations of biological phenomena. I focused on the ‘evolution on demand’ framework first because it is prominent in studies reported in the literature.

The ‘evolution on demand’ alternative framework contains six associated misconceptions, some of which are informed by anthropomorphic and teleological language (see Section 2.4.2, 33). Table 26 on page 89 highlights in light brown the six misconceptions associated with the ‘evolution on demand’ framework, and the frequencies of occurrence of these in students’ answers. While the six misconceptions associated with this framework have been explained by other researchers in evolution education (e.g. Sanders, 2014b, investigating its use in textbooks), I have not found a study that reports on the extent of students’ use of this alternative framework in their explanations of adaptation, and this section aims to fill that research gap.

The extent of students’ use of the ‘evolution on demand’ alternative framework in their explanations of adaptation was determined in two ways. Firstly, students with the two main misconceptions that are central to the ‘evolution on demand’ alternative framework, that ‘*individual organisms actively change’* and the unscientific idea that ‘*organisms change because they need to survive*’ were judged to have the framework. Secondly, students who had four or more of the six misconceptions in their explanations were judged to have the framework. Students who met either of these two criteria were considered to hold the framework, rather than just showing isolated misconceptions. The number of students with the ‘evolution on demand’ alternative framework is summarised in Table 29 on the next page.

In Table 29 the frequency counts for the number of students at each school who were judged to hold this alternative framework were derived from tables showing each student’s misconceptions, attached as Appendix G. In this appendix each student (identified by a code, for anonymity) occupies a row, and the occurrence of misconceptions is indicated by a ‘yes’ in the relevant column, for three of the four diagnostic questions. I excluded students’ responses to the *natural selection* **explanation** because natural selection can be explained without referring to adaptation, the concept on which research question d focuses. In the appendix, students with four or more misconceptions, or who mentioned the two misconceptions (highlighted in grey) that underpin the ‘evolution on demand’ framework were considered to have the ‘evolution on demand’ framework. In total, there are nine tables in Appendix G, one for each question for each school.

Table 29 summarises the frequency of students identified in Appendix G as having an ‘evolution on demand’ framework for each of the three adaptation-related questions, reported by school, as well as for the total sample. The comprehension-level questions were more successful in identifying students’ misconceptions and the relationship between those misconceptions than the application level questions.

Table 29: Frequency of students with an ‘evolution on demand‘ alternative framework, by school

Question type	**Have EoD framework**	**Administration of the diagnostic activity relative to instruction in natural selection**								
		Before being taught natural selection				After being taught natural selection				McNemar χ^2
		School1	School2	School3	**Total**	School1	School2	School3	**Total**	
Adaptation (explanation)	Yes	7 (44%)	17 (50%)	20 (50%)	**44 (49%)**	4 (25%)	10 (27%)	16 (40%)	**30 (33%)**	*$p = 0.03$**
	No	9 (56%)	17 (50%)	20 (50%)	**46 (51%)**	12 (75%)	24 (73%)	24 (60%)	**60 (67%)**	
Insect (application)	Yes	0 (0%)	8 (24%)	11 (28%)	**19 (21%)**	2 (13%)	7 (8%)	2 (5%)	**11 (12%)**	*$p = 0.16$*
	No	16 (100%)	26 (76%)	29 (72%)	**71 (79%)**	14 (87%)	27 (92%)	38 (95%)	**79 (88%)**	
Mammal (application)	Yes	3 (19%)	5 (15%)	1 (3%)	**9 (10%)**	2 (13%)	5 (15%)	3 (8%)	**10 (11%)**	*$p = 0.90$*
	No	13 (81%)	29 (85%)	39 (97%)	**81 (90%)**	14 (87%)	29 (85%)	37 (93%)	**80 (89%)**	

* Significant at the $p \geq 0.05$ level

***Prior to learning about natural selection, students used an ‘evolution on demand’ framework more often when explaining adaptation than when applying that knowledge in the scenario-based questions*.** Before learning about natural selection, 44 of the 90 students in the sample (49%) showed evidence of the ‘evolution on demand’ alternative framework in their explanations. Lower frequencies were recorded when students applied their knowledge of adaptation in the scenario-based questions: the insect question (21%) and the mammal question (10%).

The frequency of use of the alternative framework after instruction varied, depending on the question. The total number of students displaying the ‘evolution on demand’ alternative framework in their explanation of adaptation showed a statistically significant decrease (p = 0.03) in their **explanations** of *adaptation*, a 16% decrease from 49% of the group before instruction to 33% afterwards. The changes in the insect and mammal questions were not statistically significant (p = 0.16; p = 0.9, respectively). In fact, for the answers to the mammal scenario-based question there was almost no perceptible change (from 9 students showing the alternative framework before instruction to 10 afterwards). Considering that students learned about adaptation on multiple occasions before Grade 12, it is worrying that half the student sample shows the ‘evolution on demand’ framework in their explanations of adaptation before learning about natural selection, and that a third of them retained it after learning about natural selection, the mechanism by which adaptation happens.

Interestingly, more students from School 3 maintained the framework in their post-instruction explanations of adaptation. Fifteen percent and 13% higher than School 1 and School 2 respectively.

It is difficult to determine accurately the persistence of the 'evolution on demand' framework in students' explanations of adaptation. It is tempting to measure the persistence of the 'evolution on demand' alternative framework by checking the frequency of students with the alternative framework in their explanations of adaptation before and after learning about natural selection, for the whole group, from the previous table. Table 29 shows that 49% (n=44) of students were likely to have the 'evolution on demand' alternative framework in their pre-instruction explanations of adaptation and 33% (n=30) were likely to have it in their post-instruction explanations of adaptation, an apparent retention rate of 68% (n = 14). However, there are three variables that need to be considered about these statistics, shown if the data is analysed differently, as in Table 30.

Table 30: Use of the 'evolution on demand' alternative framework in students' answers before and after learning about natural selection

Appear to display the 'evolution on demand' alternative framework	Number of students	Pre-instruction instrument ONLY	Post-instruction instrument ONLY	Both pre- and post-instruction
School 1	16 (18%)	4 (25%)	1 (1%)	3 (19%)
School 2	34 (38%)	15 (44%)	6 (18%)	3 (9%)
School 3	40 (44%)	12 (30%)	8 (20%)	8 (20%)
Total	90	31 (34%)	15 (17%)	14 (15%)

Firstly, 31 students who appeared to use the 'evolution on demand' alternative framework in their pre-instruction explanations of adaptation did not use it in their post-instruction explanations. Secondly, 15 students who did not appear to have the 'evolution on demand' alternative framework in their pre-instruction explanations used it in their post-instruction explanations, a worrying finding. Lastly, there were only 14 students (16% of the sample) who used the 'evolution on demand' alternative framework in both their pre- and post-instruction explanations, and whose use of the framework could be considered to be persistent. Driver (1981, p. 99) cites Ausubel (1968) as saying that students' alternative frameworks are "amazingly tenacious and resistant to extinction", so one might expect many more students to have the alternative framework both before and after instruction. While it may seem, from the data in Table 30, that students' alternative frameworks are neither 'tenacious' nor 'resistant' to change, it is important to bear in mind that just because a student doesn't mention a misconception to do with the 'evolution on demand' alternative framework in their explanation doesn't mean that it isn't there. Some examples from each school show students who used the framework in their pre-instruction answers but did not appear to use it in their post-instruction explanation.

Student	Pre-instruction response	Post-instruction response
GT10	"Adaptation is when organisms or animals have to adapt to their habitat in order to survive. They adapt so that they can be better with what they do to survive. They adapt to prevent being hunted. If they move from somewhere hot to cold they adapt".	"Adaptation is when an animal has been put into an environment in which they cannot survive and the only way they can survive is by mating with animals in the environment that can survive which will let the offspring adapt and survive in that environment".

WSV02	"It is the ability of something to change in order to meet its need at the given time, to change so it can survive"	"Where animals change to fit their environment"
PD08	"For a species or plant to change or adapt to a certain life style in order to survive in the area"	"Species adapting to their community and getting used to their surroundings"

While all three students, in the examples above, clearly used the 'evolution on demand' alternative framework in their pre-instruction explanation of adaptation, there isn't enough evidence to say that they used it in their post-instruction response. Therefore, the persistence of the 'evolution on demand' alternative framework for as many as 24 students in the sample from pre- to post-instruction is inconclusive. This contributes to the difficulty of determining with certainty the percentage of the sample that retains the alternative framework.

Fifteen students used the 'evolution on demand' alternative framework for the first time in their post-instruction response. While these 15 students did not use the 'evolution on demand' alternative framework in their pre-instruction answer, it does not mean that they did not believe or have the framework. There was not enough evidence in their pre-instruction answers to say for sure whether they used the framework or not. This reveals one of the limitations of written responses — the inability to probe respondents for more detail. Below is an example from each school of a student who did not seem to use the 'evolution on demand' alternative framework in their pre-instruction answer, but where it is clear in their post-instruction answer.

Student	Pre-instruction response	Post-instruction response
GT04	"I understand it to be something that occurs in living organisms helping to develop/change a feature to better suit them to their environment. This change can be genetic or artificial".	"Adaptation is the process whereby an organism adapts certain features of itself in order to survive in an ever changing environment".
WSV07	"the changing or altering to suit a specific time, place, environment. How something evolves to suiting its natural surroundings"	"Adaptation = the ability of an organism to change according to their environmental and environment changes. How an organism changes to suit its environment".
PD19	"undergoing change to become suited for a certain environment"	"an organism changing its way of survival to suit its environment over a period of time"

Fourteen students used the 'evolution on demand' alternative framework consistently in their pre- and post-instruction explanations of adaptation. Of the 90 students who took part in this study, just 14 used the 'evolution on demand' alternative framework consistently between pre- and post-instruction administrations of the diagnostic activity. It is likely that actual numbers of students with this framework is higher than this number, for reasons already mentioned. The consistent use of the framework in both pre- and post-instruction **explanations** of *adaptation* illustrates just how problematic 'evolution on demand' thinking can be for understanding science. Even after learning about natural selection, some students still explain adaptation using unscientific language and with unscientific ideas.

Student	Pre-instruction response	Post-instruction response
GT09	"Adaptation is when the environment changes and when climate changes and plants and animals need to learn how to adapt to the new environment or the new climate within the region they are in"	"Adaptation is when something has happened to the environment and the animals have to adapt to the new environment. It can also be when there has been a sudden change and the animals or species have to adapt to the new environment they went to"
WSV08	"how a living organism modifies itself in order to survive in a specific environment"	"When an organism evolves itself to survive in a new environment or one that is changing. By changing certain characteristics of themselves"
PW30	"adaptation refers to how an organism is able to change itself in order to survive in an area"	"Adaption is when an animal/organism can change themselves in order to survive in their lifetime"

While the persistence of the 'evolution on demand' alternative framework is easily identified in the quotes above, based on the repeated misconceptions of the three students (each from a different school), it is not easy to know for sure. This is due to inadequate information provided by students in their answers, which leads to an inconclusive judgment about whether or not they have the 'evolution on demand' alternative framework.

If researchers (or teachers) desired to know if, or how many, students had the 'evolution on demand' alternative framework, it would be worth engaging in an oral discussion where the teacher can probe and seek clarity on students' answers. Trying to decipher such detail from students' written responses is difficult at best.

4.4.2 The less common use of three other alternative frameworks

Besides the 'evolution on demand' alternative framework, three other alternative frameworks to do with evolution were identified in the literature. I also noted them in the answers of a few of the students in this study.

'Survival of the fittest' or 'adapt or die' alternative framework

The 'survival of the fittest' alternative framework was commonly used in students' **explanations** of *natural selection*, as shown in the pink section of Table 31. I considered students to have the 'survival of the fittest' alternative framework if they combined two particular misconceptions, that *Individuals with advantageous traits WILL survive* and *those with less advantageous traits WILL die / become extinct,* or if they mentioned four or more related misconceptions in their answer. The two named misconceptions above epitomise the thinking of those holding the 'survival of the fittest' alternative framework. According to these two criteria, the number of students with the framework before and after being taught about natural selection is shown in Table 31.

The frequencies given in Table 31 have been calculated for the cohort in each school. School 1 has 16 students, School 2 has 34 students and School 3 has 40 students. Total frequencies for the whole sample (n = 90) are shown in the slightly more darkly shaded columns. Table 31 presents data specific to students **explanations** of *natural selection* because it was in this question that students were more likely to use the misconceptions specific to the 'survival of the fittest' framework than the other three questions (the last seven misconceptions, shaded in pink, in Table 26 on page 89).

Table 31: The number of students with 'survival of the fittest' alternative framework

Question type	**Have SoF framework**	**Administration of the diagnostic activity relative to instruction in natural selection**								
		Before				After				McNemar χ^2
		School1	School2	School3	**Total**	School1	School2	School3	**Total**	
Natural selection (explanation)	Yes	5 (31%)	6 (18%)	4 (10%)	**15 (17%)**	3 (19%)	11 (32%)	10 (25%)	**24 (27%)**	*p = 0.09*
	No	11 (69%)	28 (82%)	36 (90%)	**75 (83%)**	13 (81%)	23 (68%)	30 (75%)	**66 (73%)**	

The frequency of the 'survival of the fittest' alternative framework before natural selection instruction is generally low. Only a handful of students from each school used the the 'survival of the fittest' alternative framework. In total, this framework was used by only 15 (17%) of the students in the sample.

A higher percentage of the students at School 1 displayed the framework than at the other two schools: The incidence of the 'survival of the fittest' alternative framework was 13% higher in School 1 than in School 2, and 21% higher than School 3. Many of the students in School 1 had learned about natural selection in Grade 10, although the section is not mentioned in the South African Natural Sciences or Life Sciences Curriculum and Assessment Policy Statement until Grade 12. These students may have heard their teacher describe natural selection using the phrase ‘survival of the fittest’.

What Darwin, scientists, and teachers understand by the phrase ‘survival of the fittest’ is often completely different to the way students understand it. ‘Survival of the fittest’, coined by Herbert Spencer and used by Darwin in his 5th edition of the *Origin* as a synonym for natural selection, is a metaphor that is often misunderstood by students because it contains paradoxical jargon words like *survival* and *fittest* (Sanders, 2014a)*.* Sanders notes that the word *survival*, as Darwin intended for it to be used, refers to the well-being of populations and not to the survival or death of individual organisms, whilst the term *fittest* refers to the reproductive success of organisms within a population (Sanders, 2014a). However, research shows that students often believe *fittest* to refer to the physical strength, speed, or intelligence of individual organisms (Bishop & Anderson, 1990; van Dijk & Reydon, 2010). Therefore, it is unhelpful to use the phrase ‘survival of the fittest’ to explain natural selection without first defining what is meant by *survival* and *fittest* in the context of science.

Another phrase commonly used to explain natural selection is *adapt or die.* This phrase also contains paradoxical jargon terms that are easily misunderstood by students. Not all organisms without a favourable feature will *die* (Sanders, 2014a). The word *adapt* is often misunderstood to refer to changes in individual organisms that occur during their lifetime rather than to populations of organisms over many generations (Sanders, 2014a). As such, some students erroneously believe that if an organism doesn’t adapt it will die. For individual misconceptions associated with the two metaphors mentioned above, see Table 26, section 4.3, on page 89.

The frequency of the ‘survival of the fittest’ alternative framework increased in frequency post-instruction on natural selection. The incidence of the 'survival of the fittest' alternative framework increased from pre- to post-instruction by 10% for the whole group, although this difference was not statistically significant at the traditionally used 5% level ($p = 0.09$). While teaching natural selection, textbooks and teachers may have used the phrase ‘survival of the fittest’, hence the increase in the number of students with the framework. While some students may have understood it as a metaphor, others may have taken it literally, so it is important that teachers explain the implications of its literal misuse.

The percentage incidence of the survival of the fittest framework decreased in School 1 after instruction, but showed increases in both School 2 and School 3*.* The frequency of this framework among students at School 1 decreased by 12% of the students at the school, but School 2 and School 3 saw increases of 14% and 15% respectively. I think it is important that teaches are made aware of the problems with defining natural selection as the ‘survival of the fittest’ so that they can address it in the classroom to avoid students developing the 'survival of the fittest' alternative framework.

Lamarckism

Lamarckian thinking is identified by two unscientific ideas (see section 2.4.2, p. 35). The first is the ‘inheritance of acquired characteristics’, which suggests that organisms pass on to their offspring any adaptations developed during the parents’ lifetime. Although no students in my study made this mistake in the *adaptation* **explanations** and fewer than seven students in each of the scenario-based questions, the matter is a common problem mentioned in the literature (e.g. Bishop et al., 1990; Tamir & Zohar, 1991; Yates & Marek, 2015). Examples from students’ responses from my study are provided below:

> “…The soot and smoke got into the pigment of their body covering, the black colour became part of their genes. These genes were also transferred to offspring during reproduction” (WSV34).

> “This adaptation of then holding their breathe [sic] longer was then passed down to their offspring. Offspring could hold their breathe [sic] longer, therefore the seals adapted” (WSV30).

The second Lamarckian idea, ‘use and disuse’, unscientifically purports that a feature of an organism increases in strength or size with frequent use or, conversely, a feature decreases in size or gets weaker, potentially disappearing, when the individual organism no longer uses it (Brumby, 1984; Settlage, 1994). The context of the questions may have affected the frequency of this particular misconception, as it was found only in the elephant and seal ‘mammal’ questions, although for fewer than ten students in each case. It did not appear in students’ responses to the ‘insect’ questions’ (peppered-moth or the fruit chafer beetle). Examples from my study included:

> “When elephants had small ears they would flap their ears to cool themselves down. Over the years their ears started to stretch and get bigger because of all the flapping that had occurred over the years” (PD01).

> “The newer seals developed larger lung capacity in order to catch fish by staying under water for longer” (PD20)

The essentialist alternative framework

Essentialism has been cited by several authors as an obstacle to an understanding of evolution (Allmon, 2011; Herrmann, French, DeHart, & Rosengren, 2013; Shtulman, 2006). This framework can be identified by two misconceptions: 1) that species do not change over time and, 2) that all organisms in a population/species are inherently the same, that there is no variation in a population (Heddy & Sinatra, 2013; Shtulman & Schulz, 2008). Essentialist beliefs are problematic because they stand in opposition to understanding natural selection (Shtulman, 2006; Shtulman & Schulz, 2008). Essentialist beliefs become a part of students’ mental frameworks at an early age and appear difficult for students to overcome (Shtulman, 2006). Essentialism was not a frequent problem in this study, being identified in only three students’ answers:

> “Elephants are born big animals and have big ears” (WSV29).

> “The term adaptation means features of an animal or plant are specifically designed for that animal or plant in order for it to survive and thrive in its environment” (GT01).

> “The first seals hunted shallow water fish so, they could only stay under water for a short time since that is how their body (and respiratory tract) is designed” (WSV34).

The first and last student (WSV29 and WSV34) have the idea that all organisms in a population share the same characteristics. The middle student (GT01) seems to emphasise the erroneous idea that because all organisms were designed a certain way, they cannot change.

4.4.3 Concluding remarks for this section

This section explained the extent of students' use of multiple alternative frameworks in their responses to adaptation-related questions before and after learning about natural selection. This section has shown that the 'evolution on demand' alternative framework is the most common and problematic alternative framework to students' understanding of biological adaptation. However, significant reductions in the frequency of students with this framework were seen from pre- to post-instruction, showing that the teaching of natural selection reduced students' reliance on this alternative framework to explain adaptation. The 'survival of the fittest' alternative framework was more commonly found in students' post-instruction explanations of natural selection. 'Survival of the fittest' has been shown to be a problematic metaphor that textbooks and teachers ought to use with caution as some students take it literally, rather than in its intended figurative sense.

4.5 THE USE OF ANTHROPOMORPHIC AND TELEOLOGICAL LANGUAGE

4.5.1 Evidence of anthropomorphic and teleological thinking in students' answers

The following section answers research question e, restated below for convenience:

Question e: To what extent do the students use anthropomorphic and teleological language in their explanations of adaptation?

Teleology and anthropomorphism are intuitive ways of thinking and speaking, and an explanatory default for many people (see Section 2.4.3, p. 36). The frequency with which students made use of teleological and anthropomorphic phrases in their pre- and post-instruction answers is given in Table 32, revealing a number of trends.

Table 32: Frequency of anthropomorphism and teleology in students' responses

Question	Pre-instruction frequency	Post-instruction frequency	Change ↑ or ↓	p=
Teleology				
Adaptation	75 (83%)	60 (67%)	16%↓	0.01*
Peppered moth / fruit chafer beetle	61 (68%)	39 (43%)	25%↓	0.001*
Elephant / seal	72 (80%)	51 (57%)	23%↓	0.0002*
Anthropomorphism				
Adaptation	35 (39%)	23 (26%)	13%↓	0.02*
Peppered moth / fruit chafer beetle	25 (28%)	21 (23%)	5%↓	0.23
Elephant / seal	14 (16%)	15 (17%)	1%↑	0.41
Both teleology and anthropomorphism				
Adaptation	28 (31%)	16 (18%)	13%↓	0.02*
Peppered moth / fruit chafer	20 (22%)	16 (18%)	4%↓	0.02*
Elephant / seal	12 (13%)	10 (11%)	2%↓	0.08

* Statistically significant (p ≤ 0.05)

The students were nearly twice as likely to use teleology than anthropomorphism in their explanations of adaptation, prior to instruction. Prior to natural selection instruction, 83% of the students (n = 75) phrased their **explanations** of *adaptation* using teleological language. More than two thirds of students' responses to the scenario-based questions contained teleology (68% and 80% respectively) with far lower use of anthropomorphism (28% for the insect scenarios and 16% for the mammal questions).

Less than half as many students made use of anthropomorphism (39%) compared to teleology (83%) in their adaptation explanation and in the scenario-based questions (28% and 16%, respectively for anthropomorphism compared with 68% and 80% for teleology). Coley and Tanner (2015, p. 14) also found that teleology was more likely to be found in students' responses than anthropomorphism, "both groups (biology majors and non-majors) showed the same relative ordering—agreeing most with teleological misconceptions, followed by anthropocentric and finally essentialist misconceptions". Tamir and Zohar (1991) similarly found teleological reasoning to be common among Grade 10 (71%) and Grade 12 (56%) students in Jerusalem. The frequency of teleology among the Grade 12 students in the present study is more than 12% higher than the equivalent Grade 12 students in the Israeli study. One possible reason for this is that the sample in the present study is significantly larger and thus potentially more representative of a population of Grade 12 students. Another reason may be the short length of time that students in South Africa are exposed to the teaching of natural selection, This was not mentioned in the Tamir and Zohar (1991) study. Examples of the teleological reasoning in students' answers in my study are given below:

> "They also could have changed because predators were spotting them and <u>the only way in order to survive was for them to adapt</u>" (GT11).
>
> "With the drought occurring yellow chafer beetles would be seen more due to the lack of yellow plants <u>therefore having to adapt in order to survive therefore turning green to camouflage</u>" (WSV7).

The second trend is that ***the use of teleological explanations decreased significantly in students' answers after being taught natural selection:*** Statistically significant decreases in the frequency of teleology in students' answers were seen for students *adaptation* **explanation** (p = 0.01), students response to the *insect* **scenario** (p = 0.001) and for students' responses to the *mammal* **scenario** (p = 0.0002). This suggests that the teaching of natural selection may decrease students' reliance on metaphoric language to explain natural phenomena, in spite of the fact that the teachers were probably oblivious to the problem of teleological language, and would not have specifically addressed the matter.

Students were more likely to use anthropomorphic phrases in their explanations of adaptation than in their responses to the scenario-based questions, where they applied their knowledge of adaptation**:** 39% of the students used anthropomorphic terminology in their pre-instruction **explanation** of *adaptation*, which is 11% more than for students' responses to the *insect* **scenario** (28% of the group), and 23% more than the mammal scenario (16% of the group). A similar trend is found in students' post-instruction responses, where 26% of the students used anthropomorphic terminology in their **explanation** of *adaptation*, which is 3% more than for students' responses to the *insect* **scenario** (23% of the students), and 9% more than the *mammal* **scenario** (17% of the group).

> "Adaptation <u>is the ability an animal has too adapt</u> to a specific area" (GT02)
>
> "Adaptation is the process whereby <u>an organism adapts certain features of itself</u>…" (GT04)

The use of anthropomorphic thinking displays a lack of scientific understanding and inhibits science learning (Moore et al., 2002). As Legare, Lane, and Evans (2013, p. 187) explain:

> "…we argue that a conceptual cost is associated with the tendency to anthropomorphize biological change. By applying human characteristics to animals and plants, the biological world is assigned a sense of human purpose and free will that impedes an accurate understanding of biological processes. *The natural world requires neither purpose nor free will to undergo profound change* that might well ensure its survival". (my emphasis).

***The use of anthropomorphic language decreased after being taught about natural selection*.** However, only the decreased use when explaining the term adaptation was statistically significant ($p = 0.02$). While a 13% decrease was seen in the number of students using anthropomorphic phrases in their **explanations** of *adaptation* from pre- to post-instruction, it is still concerning that a quarter of students included anthropomorphism in their explanations after being taught natural selection. However, it is unknown how many students used anthropomorphic language as an explanatory tool and how many used it because they have an anthropocentric worldview.

Of the students who used anthropomorphism in their pre- and post-diagnostic responses, the majority also included teleology: Of the 39% of students who used anthropomorphism in their pre-instruction **explanation** of *adaptation,* 31% also used teleology. Similarly, 20% of the 25% and 12% of the 14% of students using anthropomorphism in their pre-instruction responses to the *insect* and *mammal* **scenario-based** questions respectively also used teleology. This suggests that a close conceptual relationship exists between anthropomorphism and teleology, as suggested by Zohar and Ginossar (1998), who argue that teleology often implies anthropomorphism because purposeful behaviour should only be attributed to humans. Examples of answers containing both anthropomorphism and teleology are:

> "The beetles noticed a change in colour (A) on the plants. Therefore (T) they had to alter their colour (A) in order to survive" (T) (WSV2)
>
> "As time went on the beetles learnt to adapt to its environment and change colour (A) due to its new environment (T) […] in which organisms adapt themselves (A) to best suit the environment" (T) (WSV5).
>
> "Seals tried to stay under for longer and longer(A) to try get the best food" (T) (PW39)

Words and phrases like 'noticed', 'they had to', 'learnt', 'adapt themselves' and 'tried' suggest that the agent of change in these responses is not random genetic mutation or mindless natural selection but rather the intentional actions of individual organisms. To suggest that the organism is the agent of change and causes adaptive evolution is a serious error and evidence of a lack of understanding of evolution and its operation in the natural world (Moore et al., 2002). It is possible that this language is being used as an explanatory tool, but it could also be evidence of a problematic underlying framework that may prevent a scientific understanding of evolution.

4.5.2 Implications for teachers

A tension exists in evolution research between those who view teleology and anthropomorphism as useful explanatory tools (e.g. Haig, 2013; Zohar & Ginossar, 1998) and those who view them as a hindrance to learning about evolution (Mayr, 1992; Moore et al., 2002; Sanders, 2014b). While Tamir and Zohar (1991) point out that anthropomorphic formulations can be useful in making factual processes and concepts more understandable for students, Moore et al. (2002, p. 66) argue that the use of figurative language in science may result in conceptual confusion. Moore et al. (2002, p. 66) continue…

> "…the figurative ascriptions of agency which seem typical of the specialist shorthand seem to offer a compelling logic that distracts students from the complexities of accepted evolutionary theory".

The use of anthropomorphism and teleology in the classroom may be particularly problematic in the South African context where a single classroom has student representatives from a myriad of cultures and languages, and for many of whom English is a second or third language (see Clerk & Rutherford, 2000). The risk of students misunderstanding figurative language, and believing that organisms themselves are agents of change rather than natural selection being the agent for adaptation, are high (see Moore et al., 2002). With this in mind, I think it would be of greater benefit to use causal language to explain adaptation and not figurative language, an idea for which Mayr (1992) provides a strong argument. To this end, Sanders (2014b, p. 144) provides a compelling argument against lifting the taboo (raised by Zohar & Ginnosar, 1998):

> "I contend that we cannot lift the taboo—that we should in fact enforce it—because teleological and anthropomorphic thinking are likely to lead to misconceptions about the cause and process involved in biological adaptations".

Chapter 5

Critical overview of the project, and emerging recommendations

The main idea that is emphasised throughout this research project is the close conceptual relationship between the evolutionary topics of *adaptation* and *natural selection*. The fact that adaptation is taught in grades 7, 8, 10, and 11 does not mean that students have a scientific understanding of the topic. Indeed how can they if natural selection is only taught in Grade 12? This chapter summarises and provides an interpretation of the main findings of this study. In light of the interpretation of the results, recommendations are provided for various groups of stakeholders associated with the teaching of both Natural Sciences and Life Sciences in South Africa, as adaptation is taught in both subjects.

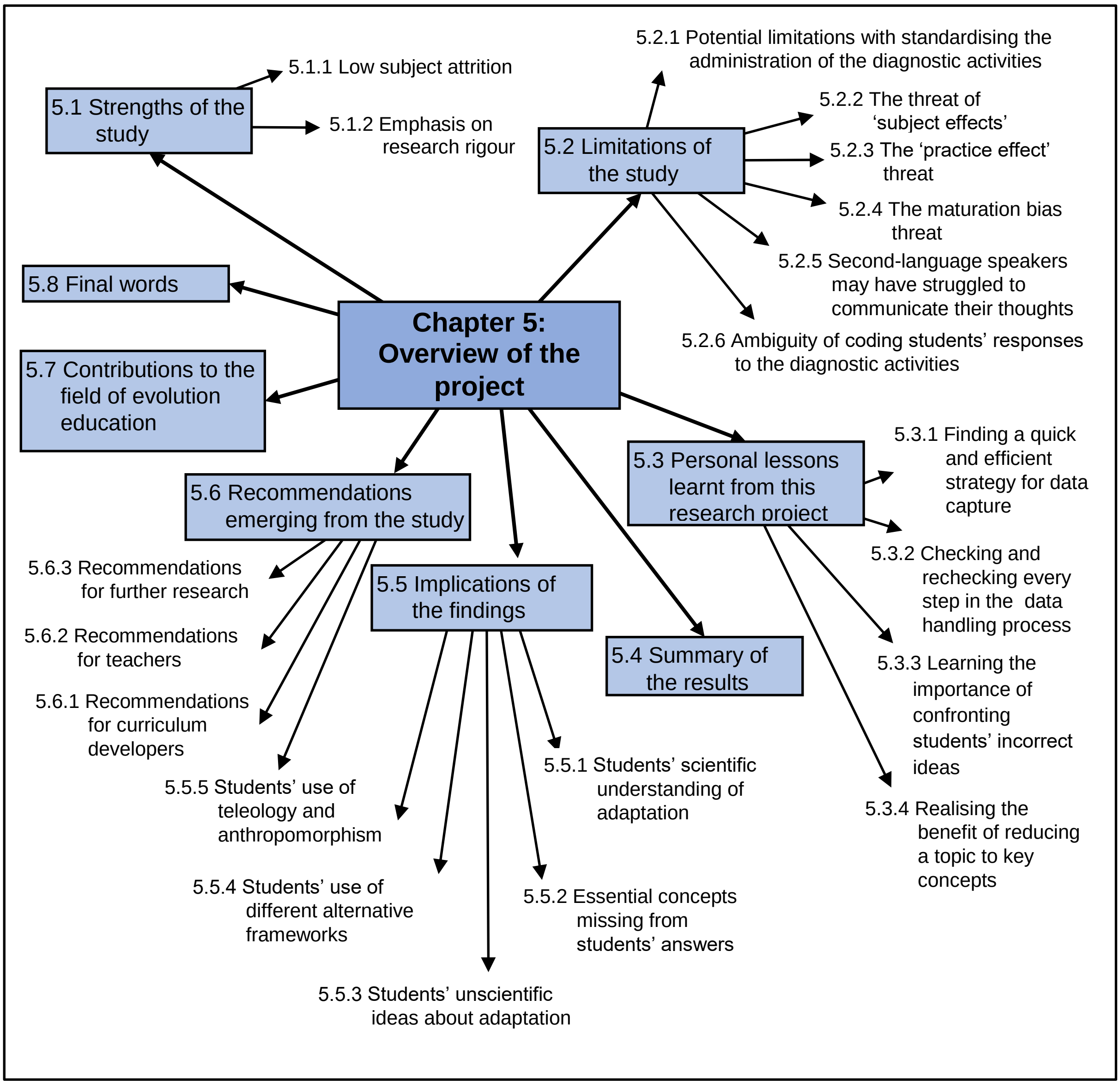


Figure 12: Structure of Chapter 5

5.1 STRENGTHS OF THE STUDY

5.1.1 The low subject attrition

While subject attrition is generally listed under the limitations of a study, I feel that a retention rate of 76% between pre- and post-instruction administrations of the diagnostic test is a strength, if compared with, for example, the relatively high attrition rate of the Jensen and Finley (1995) study (51%). Subject attrition refers to the loss of students from the sample as a result of factors such as refusal to participate or absenteeism (Cohen et al., 2005). The problem of subject attrition normally occurs in longitudinal studies that run over several months or years. Attrition of participants from the sample can cause the sample to be biased (L. Cohen et al., 2005), because, for example, it is often the weaker students who are absent, or those refusing to participate could be those with firm religious beliefs – causing the sample to be biased toward a certain kind of student. This bias, in turn, harms the generalisability of the results.

To limit subject attrition, the diagnostic test was completed as soon as possible after the topic of evolution was taught at all three schools in this study. Only one school (School B) had a high attrition (29%) from 56 students down to 40 students (see Figure 6, Section 3.2, p. 46). This was due to the topic of evolution being taught at the end of the third term just before the final Grade 12 examinations, which meant that absenteeism was high during this period at the school. School A and C had retention rates of 100% and 94% respectively.

5.1.2 The emphasis on research rigour

Much care was taken to improve the likelihood that the instruments were reliable and that the results, and the interpretation of the results, were valid. The instruments and coding schemes were face-validated on multiple occasions, sometimes by two experts, and pilot tests were conducted to ensure that the instruments functioned appropriately to gather the requisite data. The administration of the instruments was managed in such a way as to improve the likelihood that all students took part under similar standardised conditions, whether completing the diagnostic activity or answering questions in the interviews. Thereafter, the input of the data into spreadsheets, the organizing of the data within the spreadsheets, the coding, the counting of the codes, the statistical analysis, and the interpretation of the data were all double-checked, and then rechecked by an expert science education researcher. Details on research rigour are given in Section 3.7 (p. 63 – 65).

5.2 LIMITATIONS OF THE STUDY

No matter how careful a researcher is, there are often factors beyond the control of the researcher that affect the quality of a study (i.e. limitations), but they can often be restricted. The limitations of a study are the weaknesses or problems, usually beyond the control of the researcher, which may affect the results (Creswell, 2012; Price & Murnan, 2004). Identifying the limitations of a study is important for a number of reasons. Firstly, to judge the extent to which the results of the study can be generalised to "people in other situations" (Creswell, 2012, p. 199). Secondly, for the reader to be able to judge the credibility of the results so as "not to place more credit on a study's findings than is warranted" (Price & Murnan, 2004, p. 67). Thirdly, so that those who intend to do similar research or use the same or similar methods or instruments, may know where and how to improve them (Price & Murnan, 2004). While I did take precautions to minimise the effects of the limitations in this study, I realise that all research has its limitations and that some limitations are beyond a researcher's control. The following limitations were present in my study.

5.2.1 Potential limitations with standardising the administration of the diagnostic activities

The administration of research instruments, in this case a diagnostic activity, should be standardised for each participating cohort, in order to minimise reliability and validity problems (Creswell, 2012). For example, if one teacher allows their students to discuss the topic of adaptation while completing the activity, students' answers are going to be influenced by that discussion and the answers will not be an accurate reflection of what each student knows. Fraenkel, et al. (2012, p. 176) define this problem as an "implementation threat". They note that when different people are involved in the administration of an instrument, students could be treated differently, leading to the possibility of one group being advantaged over another. To minimise possible differences in the administration procedure of each school a comprehensive list of instructions, detailing the expected conditions under which students would complete the diagnostic activity (see Appendix C), was given to each teacher for both the pre- and post-instruction diagnostic activities. However, because the researcher was not present in each venue during the administration of the diagnostic activity, it is possible that the teachers might have deviated from the recommended procedure. For example, during the analysis of explanations of adaptation, two consecutive answer sheets from one school had a similar explanation of adaptation, suggesting that two students sitting next to each other may have been communicating during the activity, although they were meant to be doing it in silence on their own.

> "Adaption (sic) means that organisms are able to change their survival strategies in a favourable way in order to survive" (PW26)
>
> "Adaption (sic) is the ability of an organism to change its survival strategy in order to benefit itself" (PW27)

The underlined sections indicate similarities between the two students' answers.

5.2.2 The threat of 'subject effects'

Some research participants may not answer truthfully, or may provide answers that they think the researcher wants, rather than their own understanding (McMillan & Schumacher, 2010; Price & Murnan, 2004). Price and Murnan (2004, p. 66) note that when students say what they think the researcher wants them to say, "…their responses reflect neither their true perceptions nor the perceptions of the population from which they were drawn". The way in which students view and participate in a study has the potential to threaten the internal validity of the study (Fraenkel et al., 2012). An example of a student who appears to answer to please the interviewer is given below.

> "Scientists believe that elephants adapted from having smaller ears to now having larger ears due to evolution. This can be explained as a man known by the name of Darwin had a theory in which he explained that various animals of the same environment and habitat was mixed with various species. Therefore, they could have reproduced to form another sort of species which obtained various genetics from their parents. Or as stated in the second theory he believed that the species genetics may have changed or parts of their body may have changed to adapt to the environment and habitat as well as because they were not as important and healthy had no use or function to it". (GT05)

The reason why I think this student is answering to please the researcher is because the student seems to give every bit of knowledge she has about evolution, possibly because that is what she thinks the teacher wants.

In order to try to encourage students to answer as truthfully as possible, students were not made aware that the pre-instruction diagnostic activity was a part of a research project until after each student had completed it as part of a normal school lesson. Students were told that they needed to complete it as honestly as possible so as to help teachers identify strengths or weaknesses in students' thinking and to help teachers plan future lessons. Once students had completed the pre-instruction diagnostic activity they were informed that the written activity was a part of a research project, given letters of information for themselves and their parents, and asked if they would agree to allow their answers to be used in the study. While it was possible to delay information about the project until after the pre-instruction diagnostic activity had been completed, it was not possible for the post-instruction instrument, as all of the details about the project had already been disseminated.

5.2.3 The 'practice effect' threat

In pre- and post-test studies involving tests or activities handed out before and after an intervention, students may deliberately learn how to answer similar questions in preparation for the post-test (post-instruction diagnostic activity in this case), something Gardner and Grafen (1975) call 'the practice effect'. This is particularly problematic in studies where the same instrument is used for the pre- and post-instruction administrations. In order to minimise the influence of the 'practice effect', different but equivalent questions were developed for the **scenario-based activities** (see Section 3.4, p. 47). Preparing equivalent versions of the adaptation and natural selection **explanations** was not possible and students could have prepared how to answer these questions prior to answering the post-instruction instrument, if they remembered what had been asked – note that the pre-diagnostic exercises were not returned to the students at any stage. To minimise this potential threat, students were not made aware of the post-instruction diagnostic activity until it was handed out.

5.2.4 The maturation bias threat

Differences detected in studies that have both a pre- and post-intervention instrument, particularly if the time interval is long, may be the consequence of physical, emotional, or intellectual maturation of the research participants and not necessarily because of the intervention or teaching content (Fraenkel et al., 2012; Price & Murnan, 2004). Fraenkel et al. (2012) note that this is particularly problematic with young children, as they tend to develop quickly in the primary school and early high school years. The gap between the pre- and post-instruction activities was kept as short as possible to avoid potential maturation biases. While it is possible that some students may have matured during the two-month timespan between the pre- and post-instruction administrations of the diagnostic activity, the students involved in this study were in Grade 12, so beyond the age range identified by Frankel et al (2012) as being high-risk.

5.2.5 Second-language speakers may have struggled to communicate their thoughts

English second- or third-language speakers responding to an instrument worded in English, and that has to be answered in English, may struggle to communicate their thinking in a language that is not their mother-tongue (Fraenkel et al., 2012). The reason for this is their potential lack of vocabulary, and lack of fluency to express what they are thinking and to say what they mean. This is further complicated by the language of science, which has a jargon all of its own (Clerk & Rutherford, 2000). In this study, 22 students (25% of the sample) were English second-language speakers. Answers could reflect linguistic difficulties, rather than conceptual understanding, which could cast doubts on the validity of claims emerging from the data.

The following example illustrates how an English second-language speaker struggles to express herself, and provides an answer that is both illogical and incoherent. It is not easy to differentiate between a lack of understanding and an inability to express herself in a language that is not her mother tongue.

> "My full complete understanding of the biological term of natural selection is that various living organisms come to a simola (sic) [similar] environment where then had reproduced making that of a gene pool those organisms that were reproduced only some survived as some obtained diseases, others eaten by their predators and those who had survived and were able to reproduce continued to survive thus creating a smaller population" (GT05)

Ideally, students like this should be asked to answer such questions in their mother-tongue. However, in South Africa there are 11 official languages, and neither teachers nor researchers will be fluent in more than a few of these. For practical reasons, therefore, translating instruments into a language of students' choice is not possible.

5.2.6 The ambiguity when coding some responses to the diagnostic activities

While developing a coding scheme is relatively straightforward, the actual process of coding the data can be ambiguous. This is particularly true when distinguishing between a segment of data that is stated and one that is merely implied. When coding the unscientific idea '*individuals with the advantageous trait WILL survive'*, coding is relatively easy for students clearly stating the key phrase, '*will survive*', as seen in the following example:

> "Natural selection, is the selection of the better suited animal to survive. Through different variations in animals the better suited animal and most adapted will survive" (GT02)

Other students did not use the key phrase but implied that organisms with the trait or feature would survive:

> "It means that certain features of certain animals or plants will help it to continue living while other features will be discarded" (GT01)
>
> "Natural selection is where organisms in a population who are fittest for their environment survive" (GT14)

The problem is trying to determine whether a student is implying this unscientific idea or not. It is possible that I did not code every instance, because I did not interpret what the student was saying correctly. However, every effort was made to limit the possibility of this sort of error. To improve reliability, two coders coded the data, followed by discussions and terminating in mutual agreement if different codes were initially allocated (see Section 3.7, p. 63 - 65). Though, this does not rule out the possibility of codes being missed.

5.3 PERSONAL LESSONS LEARNT FROM THIS RESEARCH PROJECT

As a result of the work completed and time spent researching this particular topic, I have learnt many practical lessons that I hope to apply during further research and in my classroom practice.

5.3.1 Finding a quick and efficient strategy for data capture

In order to capture the data as quickly and efficiently as possible, two researchers with duplicated screens were involved in capturing the data. One researcher would focus on the codes in the students' answer and read them out aloud, while the other would scroll along the rows in the Excel spreadsheet, filling in a mark (usually in the form of a '1' to facilitate automatic counting) under the column with the relevant code. Capturing the data in this way proved more accurate and more efficient than an individual researcher capturing the codes and then going through them again to check the accuracy of the capture.

5.3.2 Checking and re-checking every step in the data-handling process

While efficiency and speed were important, so was accuracy. To improve accuracy, every step during the data handling process was checked and rechecked. While this process was tedious and often resulted in more work, through either recoding or recapturing problematic data, it was a necessary process because errors were sometimes found during the data checks. After two researchers had captured the data, a third checking process was undertaken where the spreadsheets were printed and each individual entry was checked against the codes in the student's answer, on a few occasions revealing errors in the original capturing process.

5.3.3 Learning the importance of confronting students' incorrect ideas

Confronting students with incorrect ideas is a helpful step in creating a state of disequilibrium in their thinking and to then help them toward conceptual change (Caravita & Halldén, 1994). A number of authors in the research literature (e.g. Bishop & Anderson, 1990; Stover & Mabry, 2007) recommend this strategy and I have found it useful in dealing with misconceptions in my classroom.

5.3.4 Realising the benefit of reducing a topic to key concepts

Based on the number of key concepts missing in students' answers, I have learnt that it might be helpful to reduce a definition (e.g. *biological adaptation* or *natural selection*) into a list of important concepts. Each concept can then be taught and emphasised individually so that one or two are not forgotten or left out. It might also help students to grasp the full implication of a definition. By way of example, I have placed the definition of biological adaptation in Table 33 and then listed the key concepts that students need to know to have a full understanding of the topic.

Table 33: Definition of adaptation and the important concepts needed to understand the term

Definition of adaptation	Important concepts
Adaptation is defined as a characteristic of an organism that increases it's fitness, or the process by which populations of organisms increase in fitness relative to their environment	1. Adaptation involves becoming more suited to the environment 2. Advantageous characteristics convey a survival and reproductive advantage on individuals with the trait 3. An adaptation can also be a specific advantageous characteristic (feature/ trait) 4. Adaptation is a process that occurs by natural selection 5. Adaptation occurs in populations of organisms 6. Adaptation takes many generations

Most definitions of adaptation do not point out the key concepts that are essential to fully understand adaptation. I learnt that these key concepts need to be fleshed out by a teacher so that students understand the full implication of the topic.

5.4 SUMMARY OF THE RESULTS

A detailed presentation of the results is given in Chapter 4. The data for this dissertation was looked at in accordance with the main research question and five sub-questions. A summary of the findings for each of the five sub-questions in given below.

QUESTION a: What is the nature and extent of the scientific concepts about biological *adaptation* held by the students, before and after learning about *natural selection*?

The data looking at the number of correct concepts was analysed in several ways: by group, for individuals, and by concept. While the number of correct statements in students' answers improved for all four questions, after learning about natural selection, the extent of their knowledge remained limited.

- **The mean number of correct concepts per student improved for all four questions**, **after instruction.** three improvements being statistically significant (explaining *natural selection* $p = 0.004\times10^{-5}$; insect scenario-based questions $p = 0.003\times10^{-3}$; mammal scenario-based questions $p = 0.001\times10^{-6}$).
- **The mean number of correct concepts per student remained low after instruction, for all four questions**. Of the six concepts required for completely correct answers for the explanation questions, students averaged only 1.33 correct concepts for *adaptation* before instruction and just 1.41 afterwards, and 0.14 and 0.76 for *natural selection*. Of the required eight correct concepts for each scenario-based question, students averaged 1.22 correct statements before instruction for the *insect* scenario and only 2.24 afterwards, while for the *mammal* scenario students averaged 0.57 correct statements before and just 1.92 after learning about *natural selection*.
- **The distribution of marks by mark category improved for the whole group**. Fewer students provided no answer for the *natural selection* explanation question (16% before instruction, 0% afterwards). Of those who did attempt to answer the question, fewer gave no correct statements (in total 73% gave no correct statements before instruction, and only 56% afterwards). For the *insect* scenario 34% gave no correct statements before instruction, and only 17% afterwards; and for the *mammal* scenario 65% gave no correct statments before instruction, 36% afterwards. More students provided five or more correct answers in the *insect* scenario (5% before instruction, 9% afterwards); and the *mammal* scenario (0% before instruction, 11% afterwards).
- **Individual students improved the number of correct statements in their answers for three of the four questions.** More students improved than regressed in the *natural selection* explanation (37% improved, 4% regressed after instruction); for the *insect* scenario (53% improved, 21% regressed after instruction); the mammal scenario-based question (53% improved, 8% regressed after instruction).
- **Certain concepts saw statistically significant improvements after instruction**. Three of the six correct concepts occurred significantly more often after instruction for the *adaptation* explanation (*adaptations can be advantageous*, $p = 0.023$; *adaptation occurs to populations of organisms*, $p =$

0.005; and *adaptation takes many generations*, $p = 0.014$). Three of the six correct concepts improved significantly after instruction for the *natural selection* explanation (*certain variations favour survival of the organism in its environment*, $p = 0.0001$*; individuals in a population show variation (genetic and phenotypic),* $p = 0.0005$; *by surviving longer individuals with advantageous characteristics get to reproduce so have more offspring,* $p = 0.002$). Four of the eight correct concepts improved significantly in the *insect* scenario answers (*the population shows variation of traits*, $p = 0,2 \times 10^{-5}$; *increased survival leads to more reproduction, and thus more offspring of that type*, $p = 0,2 \times 10^{-5}$; *those lacking the advantageous traits are less likely to survive*, $p = 0,005$*; there is thus a reduction of numbers of these organisms in the population*, $p = 0,04$). Six of the eight correct concepts in the *mammal* scenario-based questions saw statistically significant improvement (*Only genetically inherited traits lead to adaptation*, $p = 0,004$; *the population shows variation of traits*, $p = 0,3 \times 10^{-4}$; *Advantageous traits lead to increased survival*, $p = 0,9 \times 10^{-4}$; *increased survival leads to more reproduction, so more offspring of that type*, $p = 0,3 \times 10^{-4}$; *reduction of numbers of these organisms in the population*, $p = 0,3 \times 10^{-5}$; *over many generations,* $p = 0.02$).

QUESTION b: What essential concepts are missing from students' explanations of biological *adaptation*, before and after learning about *natural selection*?

The data looking at the correct concepts missing from students' answers was analysed by concept for the whole group. Concepts essential to a scientific understanding of *adaptation* were missing from students' responses to all four questions.

- **Three correct concepts were missing in more than 90% of the group for the *adaptation* explanation, both before and after instruction**: *adaptation as a process that occurs by natural selection* (missed by 99% before, 97% after instruction); *adaptation occurs in populations* (100% before, 91% after instruction); *adaptation takes generations to occur* (100% before, and 93% after instruction).
- **More than 90% of students missed all six correct concepts in the *natural selection* explanation question before instruction**. Three of these concepts saw statistically significant reductions after instruction: *certain variations favour survival of organisms in their environment* (91% before, 64% after; $p = 0.0001$); *individuals in a population show variation* (98.9% before, 83.4% after; $p = 0.0005$); *by surviving longer individuals with advantageous characteristics get to reproduce, so tend to have more offspring* (99% before, 87% after; $p = 0.002$). The other three (that *individuals that lack advantageous traits are less likely to survive*; *advantageous traits will be passed on to more offspring in the next generation than less advantageous traits*; and *the proportion of advantageous traits increases in the population*) were still missing in at least 90% of students' answers after instruction.
- **Fewer correct ideas were missing from students' responses to the *insect* and *mammal* scenarios after instruction**. The teaching of natural selection appears to reduce the number of missing concepts in students' answers. The largest reductions in missing concepts were: *populations show variation of traits* (28.8% reduction for the *insect* scenario, and 24.4% for the *mammal*); *increased survival increases the chances for reproduction, resulting in more offspring of that type* (15% reduction for the insect question, and 25.6% for the mammal); *there is a reduction in the frequency of individuals with less advantageous traits in the population* (15.6% reduction for the *insect* scenario, and 25.6% for the mammal).

QUESTION c: What is the nature and extent of the students' unscientific ideas about biological *adaptation*, before and after learning about *natural selection*?

When looking at the extent and nature of students' unscientific ideas, the data was analysed by unscientific idea for the whole group. Totals for each unscientific idea before and after instruction, and the number of misconceptions in students' answers by category, were looked at. Results were variable: statistically significant decreases were seen in some unscientific ideas, after instruction, and statistically significant increases were seen in others.

- **All of the top six unscientific ideas (all associated with the 'evolution on demand' alternative framework) decreased in total number after instruction, four of the decreases being statistically significant**: *adaptation is caused by environmental changes* (169 occurrences across all four questions before instruction, 136 after instruction; $p = 0.002$); *adaptations are needed in order to survive* (152 before instruction, 132 after instruction; $p = 0.049$); *individual organisms adapt* (100 before instruction, 79 after instruction; $p = 0.025$); *organisms are aware of their need to change* (84 before instruction, 61 after instruction; $p = 0.012$).
- **Six of the seven unscientific ideas associated with the 'survival of the fittest' alternative framework increased after instruction, although only two of the increases were statistically significant**: *Those with less advantageous traits die / become extinct* (32 before, 63 after; $p = 0.000004$); *individuals with advantageous traits will survive* (24 before, 41 after; $p = 0.002$).
- **The distribution of unscientific ideas by mark category showed a slight improvement**: Increases in the lower mark categories resulted from decreases in the higher mark categories from pre- to post-instruction, indicating lower frequencies of unscientific ideas. Fewer students had five or six misconceptions in the *adaptation* explanation (34% before instruction, 21% after) and for the *insect* scenario (24% before, 17% after instruction). More students had two or fewer unscientific ideas in the *adaptation* explanation (29% before, 44% after) and *natural selection* explanation (53% before, 57% after), and the *insect* (31% before, 46% after) and *mammal* scenarios (33% before instruction, 39% after).

QUESTION d: To what extent do students exhibit alternative frameworks when explaining adaptation?

Students' answers were analysed for four alternative frameworks, 'evolution on demand', 'survival of the fittest', 'Lamarckism' and 'essentialism'. The analysis was carried out on the whole sample and for each school.

- **More students revealed the 'evolution on demand' alternative framework in their explanation of *adaptation* than when they applied their knowledge in their application-based responses to the scenario questions:** Nearly half of the student sample (49%) used the 'evolution on demand' alternative framework in their pre-instruction explanations of *adaptation* as compared to just below a quarter (21%) in the *insect* scenario and just under one tenth (10%) in the *mammal* scenario. Similarly, a third of students (33%) made use of the 'evolution on demand' alternative framework in their post-instruction explanation of *adaptation* as opposed to a little more than a tenth in both scenario questions (13% insect scenario, 11% mammal scenario).

- **Some students used the 'evolution on demand' alternative framework in both their pre- and post-instruction explanations of adaptation:** fourteen percent of the student sample used the 'evolution on demand' alternative framework consistently in their pre- and post-instruction explanations of *adaptation*.
- **More students (27%) used the 'survival of the fittest' alternative framework after instruction than before instruction (17%) in their explanations of natural selection:** Nine more students used the 'survival of the fittest' alternative framework after instruction than before instruction in their *natural selection* explanation. This did not prove to be statistically significant (*p* = 0.09)
- **Lamarckian thinking occurred infrequently in students' responses**: The two misconceptions associated with this framework (*inheritance of acquired characteristics* and *use and disuse*) were found only in students' responses to the scenario-based questions and in fewer than ten students' responses each time.
- **Essentialism was uncommon in students' responses:** after reviewing all eight answers on the two administrations of the instrument, only three instances of essentialism were found.

QUESTION e: To what extent do the students use anthropomorphic and teleological language in their explanations of adaptation?

Students' use of teleology and anthropomorphism were analysed for the *adaptation* explanation question and the *insect* and *mammal* scenario questions (being the three questions needing answers relating to adaptation). Analysis of both before and after instruction answers revealed that students were more likely to use teleology than anthropomorphism.

- **Students commonly used teleology in their pre-instruction answers to all three adaptation-related questions:** The majority of students used teleology in their pre-instruction explanations of *adaptation* (83%) and in their pre-instruction responses to the *mammal* scenario question (80%). Fewer students (68%) used teleology in their pre-instruction response to the *insect* scenario question.
- **Students used anthropomorphism more frequently in their pre-instruction *adaptation* explanations than in the scenario questions**: Thirty-nine percent of the group used anthropomorphism in their pre-instruction *adaptation* explanation, but only 28% in the pre-instruction *insect* scenario and 16% in the pre-instruction *mammal* scenario answers.
- **Students who used anthropomorphism in their pre-instruction answers were also likely to use teleology:** Of the 35 students (39% of the sample) who used anthropomorphism in their pre-instruction explanation of *adaptation,* 28 students (31% of the whole sample) also used teleology. Similarly, 20 (22%) of the 25 students (28%) who used anthropomorphism also used teleology in their responses to the *insect* scenario question, and 12 students (13%) of the 14 students (16%) who used anthropomorphism in their responses to the *mammal* scenario-based question also used teleology.
- **Students' use of teleology showed statistically significant decreases after instruction, but remained common in students' answers:** Teleology use declined by 16% (*p* = 0.01) for the *adaptation* explanation question, by 25% (*p* = 0.001) for the *insect* scenario and by 23% (*p* = 0.0002)

for the *mammal* scenario after instruction. This was in spite of the fact that no teachers specifically addressed the matter of teleology use.

- **Students' post-instruction use of anthropomorphism decreased significantly in their adaptation explanations but showed decreases (although not statistically significant) for the scenario-based questions:** *Adaptation* explanation (39% before, 26% after, *p* = 0.02); *insect* scenario (28% before, 23% after, *p* = 0.23); *mammal* explanation (16% before, 17% after, *p* = 0.41).
- **Fewer students used teleology and anthropomorphism together in the same answer after instruction:** Teleology and anthropomorphism were used concurrently for the adaptation explanation (by 31% of the sample before instruction, but in only 16% of the sample after instruction; *p* = 0.02); in the *insect* scenario (22% before, 18% after; *p* = 0.02); and for the *mammal* scenario (13% before; 11% after; *p* = 0.08). The level of change was statistically significant for the *adaptation* explanation and the *insect* scenario and close to the *p* = 0.05 level of significance for the *mammal* scenario. This suggests that the teaching of natural selection has a positive effect on reducing the combined use of anthropomorphism and teleology in students' responses.

5.5 IMPLICATIONS OF THE FINDINGS

The previous section presented a summary of the results. In this section these results are discussed.

5.5.1 Students' scientific understanding of adaptation

Although students' explanations of *natural selection* improved significantly after learning about natural selection, their ability to explain *adaptation* improved little. One reason might be that, even though the two topics are inextricably linked in biology, the South African Life Sciences Curriculum and Assessment Policy Statement does not link the topics of adaptation and natural selection, so teachers are unlikely to teach the relationship between the two concepts. However, students' ability to explain *adaptation* in the scenario-based questions showed statistically significant improvements for some of the important concepts considered necessary to understand adaptation. Even though students were not aware that they were explaining adaptation in the scenario questions, an improved understanding of natural selection improved their ability to explain adaptation by referring to the mechanism of natural selection. An age-appropriate explanation of natural selection in earlier grades (advised by Legare et al., 2013; and Shtulman et al., 2016), when adaptation is taught, might help students understand this difficult concept in biology better.

5.5.2 Essential concepts missing from students' answers

Only one of the six key scientific ideas about adaptation (*adaptation involves becoming more suited to the environment*) was missed by fewer than half of the sample in their pre-instruction explanations. The frequency of missing statements in students' explanations about adaptation for the other five statements on the pre-instruction instrument varied between 61% and 100%. Adaptation is a topic that is taught for a number of years prior to Grade 12, yet five of the six statements that define the topic are missing in the majority of students' responses. Similarly, five of the eight key statements, were missed by 80% or more of the students in their pre-instruction responses to the scenario-based questions. Part of the reason for students' poor understanding of adaptation is their lack of knowledge and apparent difficultly understanding the process of natural selection. Even after natural selection instruction, five of the six key natural selection concepts were missing in more than 80% of students' answers. However, the problem is not only a South African problem. For example, a British study of 83 12 to 16 year old students showed that only 1 out of 10 students gave an acceptable science definition of adaptation. Although the Engel Clough and Wood-Robinson (1985a) study did not identify specific concepts that students were missing but, they did point out that only 12% of their sample understood that biological adaptation results from natural selection operating on a population. Because of the strong conceptual links between adaptation and natural selection (as explained in Section 2.3.5, p. 24), it is logical to assume that the frequency of missing concepts in students explanations of adaptation and in their responses to the scenario questions would be greatly reduced if natural selection was taught when adaptation is first introduced as a topic in the South African Natural Sciences curriculum in Grade 7 or 8. The early inclusion of natural selection concepts in Natural Science is a theme that comes through strongly from a number of well-respected biology education researchers (e.g. Kelemen, Emmons, Schillaci, & Ganea, 2016; Legare et al., 2013; Shtulman et al., 2016). Engel Clough and Wood-Robinson (1985a, p. 129) argue that, “it is possible that rather than delaying the teaching of evolution beyond 16 years, we need to include it much earlier in the secondary science curriculum”.

The large number of missing concepts in students' answers also has implications for the development of scientific literacy. Scientific literacy involves “developing the ability to creatively utilise sound science knowledge in everyday life or in a career, to solve problems, make decisions and hence improve the quality of life” (Holbrook & Rannikmae, 2009, 281). Evolution contributes to scientific literacy because it has multiple applications in our everyday lives, such as agriculture and medicine and because it is an explanatory framework that “brings great order and coherence to our understanding of life” (National Academy of the Sciences, 1998, p. 3). The importance of scientific literacy is further discussed in Section 1.1.1 (p. 3).

5.5.3 Students' unscientific ideas about adaptation

Of the thirteen most frequent misconceptions identified in students' responses on the diagnostic activities, five saw statistically significant decreases, although two saw statistically significant increases after instruction. The teaching of natural selection appears to reduce the number of misconceptions in students' answers to the adaptation explanations and to the scenario-based questions. This is likely because, as Mayr (1992, p. 135) put it “natural selection provides a satisfactory explanation for the cause of organic evolution” and, after learning about natural selection students are better able to provide causal, rather than teleological or anthropomorphic, explanations for biological phenomena. Certain misconceptions in students' explanations (e.g. *organisms with less advantageous traits die / become extinct* and *individuals with advantageous traits WILL survive*) of natural selection increased in frequency after instruction. Errors in the curriculum documents are often repeated in the textbooks or by teachers in the classroom. There is also the possibility that the increase in some unscientific ideas may be caused spontaneously without any obvious outside source or error (J. D. Coley & Tanner, 2012). Whatever the cause, levels of unscientific ideas about adaptation and natural selection remain common in students' thinking, even after instruction (see Bishop & Anderson, 1990; Brumby, 1984; Engel Clough & Wood-Robinson, 1985a). This has serious implications for stakeholders; recommendations are made in Section 5.5.

5.5.4 Students’ use of different alternative frameworks

I looked for four alternative frameworks identified in the literature, in students’ responses to both the pre- and post-instruction diagnostic activities. The 'evolution on demand' alternative framework was the commonest alternative framework in students’ explanations of adaptation and in their pre- and post-instruction responses to the scenario questions. Students tend to think that an organism initiates a change when it sees changes in the environment, or that an individual organisms will consciously adapt during their lifetimes when their survival is threatened (see Section 2.4.2, p. 34). To identify the framework in a student’s answer, the student would need to mention multiple misconceptions. However, it is possible that a student’s clumsy wording (either because they are a second language English speaker, or because they don’t have the vocabulary to describe the phenomenon) could result in the misdiagnosis of the framework in a students’ thinking. After instruction, students would have learnt the necessary vocabulary and the mechanism of natural selection reducing their reliance on alternative unscientific ideas. This could account for the reduction in this framework seen in post-instruction responses.

The ‘survival of the fittest’ framework was commonly found in students’ post-instruction responses. Students tend to associate natural selection with the phrase ‘survival of the fittest’ because the phrase is often used as a synonym for natural selection (Gregory, 2009; Rees, 2007). However, there are pitfalls associated with the use of the phrase, especially the ambiguity of the words ‘survival’ and ‘fittest’. Students tend to erroneously assume that the most physically fit survive (see Section 2.4.2, p. 34). Of particular concern is the fact that in this study the ‘survival of the fittest’ alternative framework became more prevalent among the sample after the teaching of natural selection. This could be the result of incorrect information in the description of natural selection in the previous Revised National Curriculum Statement which said, “Natural selection kills those individuals of a species which lack the characteristics that would have enabled them to survive and reproduce successfully in their environment” (Department of Education, 2002, p. 64). This statement makes natural selection look like a premeditated murderer that annihilates the weakest and lets the strongest live, instead of the “blind, non-intentional mechanism” (Kelemen, 1999, p. 467) that it is. Errors like this one are often perpetuated by textbooks and teachers who have to teach the errors even though they know it is an error (Tshuma & Sanders, 2015). Teachers need to take greater care when teaching and not suppose that information in textbooks or even the curriculum documents is correct (see recommendations, Section 5.5).

The Lamarckian alternative framework (see Section 2.4.2, p. 35) with its two associated misconceptions, soft-inheritance and ‘use and disuse’, is reported to be a common problem in the literature (see Bishop & Anderson, 1990; Cunningham & Wescott, 2009) but wasn’t commonly found in this study either before or after instruction. It is possible that the context of the questions in this study influenced the sorts of answers students gave and thus Lamarckian answers were not common. The Grade 12 Life Science curriculum also requires a comparison between Darwin’s and Lamarck’s theories which could explain the few Lamarckian misconceptions in students post-instruction explanations as well (see Department of Basic Education, 2011b, p. 61).

Essentialism is the final framework that was looked for in students’ answers in this study (see Section 2.4.2, p. 35). The literature points out that Essentialism was found to be a common problem in young children, negatively affecting their understanding of evolution (Pobiner, 2016; Shtulman, 2006). It was not commonly found in students' responses in this study. Essentialism was likely not commonly found in this study because these students are between 17 and 19 years of age (therefore not young students) and because they had been through the Grade 12 genetics course, before learning about evolution, where they would have learned about genotypic and phenotypic variation (the antithesis of essentialism).

5.5.5 Students' use of teleology and anthropomorphism

Students commonly made use of anthropomorphism and teleology in their explanations of adaptation and in their responses to the scenario-based questions. While some reductions were seen in students' post-instruction answers, levels of teleology and anthropomorphism remained high. Multiple authors show that teleology and anthropomorphism are natural ways of thinking that develop intuitively from a young age and persist into adulthood for most people (J. D. Coley & Tanner, 2012; Gregory, 2009; Legare et al., 2013). Some researchers even recommend the use of these ways of speaking (e.g. Tamir & Zohar, 1991). The concern over the use of such language is that some students tend to take figurative language literally (Jungwirth, 1975) which can result in conceptual confusion, especially when teleological and anthropomorphic phrases appear to contradict causal explanations of natural selection and adaptation (Anderson et al., 2002; Mayr, 1992). In the case of adaptation, teleology and anthropomorphism might be causing misconceptions associated with the 'evolution on demand' alternative framework because anthropomorphising the individual can imply thought, control and forward thinking (Sanders, 2014a). As such, teachers and textbook authors need to be aware of the problems surrounding the use of such language and ought to explain it or leave it out entirely. This is discussed further under the recommendations, Section 5.6.

5.6 RECOMMENDATIONS EMERGING FROM THE STUDY

Twenty-five years ago Settlage (1994. p. 449) pointed out that evolution is essential to an understanding of biology, "and yet true comprehension of the process consistently eludes students". Many students have been shown to hold onto their naïve conceptions even after being taught the mechanistic explanations for the occurrence of certain phenomena (Bishop & Anderson, 1990; Engel Clough & Wood-Robinson, 1985a; Settlage, 1994). Such naïve conceptions or misconceptions prevent new learning which will negatively affect a student's academic performance in the short term, but also limit their contribution to society in science-related fields in the long term. To this end, the recommendations from this study apply to the four groups of stakeholders with input into students' learning; curriculum developers, teachers, textbook writers, and researchers. As Edelson (2002, p. 119) notes:

> "At its heart, education is a design endeavor. Teachers design activities for students, curriculum developers design materials for teachers and students, administrators and policymakers design systems for teaching and learning. If the ultimate goal of educational research is the improvement of the education system, then results that speak directly to the design of activities, materials, and systems will be the most useful result".

All of the stakeholders inform educational design and are essential to the improvement of the educational system. As such, this section discusses how the findings will be made known to each group of stakeholders.

5.6.1 Recommendations for curriculum developers

Curriculum developers are responsible for developing curricula, working with teachers and other stakeholders to implement the curriculum and to recommend changes or revisions to existing curricula (Edelson, 2002). I have chosen to address recommendations arising from this study to curriculum developers first because teachers take their cue of what to teach from the curriculum document. Although teachers play a significant role in influencing students' understanding of topics, unless the curriculum changes, real and lasting educational change is unlikely. Textbook authors also write according to the information contained within the curriculum documents, which both teachers and students rely on (Hutchinson & Torres, 1994), and often perpetuate errors found in the curriculum documents (Tshuma & Sanders, 2015). Therefore, educational change starts with curriculum developers.

Curriculum developers will be targeted when the next curriculum review takes place. For curriculum changes to occur, the education minister needs to sanction a ministerial task team to review the curriculum. Once the task team has been set up, consultative forums are usually put in place to obtain input from various stakeholders including teachers, politicians, teacher unions, non-governmental organisations and academics from higher learning institutions (De Villiers, 2011). Engaging in and contributing to the consultative process of future curriculum revision is an important outcome of this dissertation.

Recommendation 1: the curriculum documents could do more to differentiate between adaptation as a product and adaptation as a process. The literature points out that there are two facets to the topic of adaptation, as both a process and as a product. However, this research project has shown that students are confused about whether adaptation is a process, product or both. The majority of the sample in their pre-instruction responses say or imply that adaptation is a process (80%), a little over a third of the students (37.4%) say or imply that it is a product, and less than 30% say that is both. The students that stated or implied that adaptation is a process did so because the word implies a change in something in relation to something else (Ghiselin, 1966). Students who said that it was a product or characteristic are likely to have learnt this from the teaching of adaptation in the classroom as the references to adaptation in the curriculum documents focus on adaptation as a characteristic (see Table 2, Section 1.3.1, p. 5). To understand adaptation correctly, students need to know that it is both a process that occurs to populations over generations by natural selection, and a product or characteristic that individual organisms have that improves their chance of survival and reproduction in their environment. It is important that the curriculum documents reflect this. The logical place to include this information would be in the Grade 8 Natural Sciences curriculum when adaptation is first introduced as a topic.

Recommendation 2: it seems logical to recommend that natural selection, even if it is a simplified version, be taught when adaptation is first introduced as a standalone topic in the Grade 8 Natural Sciences curriculum. The results of this study have shown that a close conceptual link exists between adaptation and natural selection. For example, this study has shown that students' correct ideas about adaptation in the post-instruction scenario questions improved (some statistically significantly) and the number of misconceptions in students' responses to the post-instruction scenario questions decreased, some of them statistically significantly, after learning about natural selection.

Recommendation 3: common misconceptions about the topic of adaptation could be included in the curriculum documents as a tool to confront and address common misconceptions about adaptation. This research project has shown that the majority of students had misconceptions about the topic of adaptation, especially those associated with the 'evolution on demand' alternative framework (see Section 4.3, p. 88). From the research literature on human thinking (Cunningham & Wescott, 2009; Pobiner, 2016), it is likely that many of the misconceptions that came through in students' responses to the diagnostic activities developed in students' thinking prior to instruction. While some teachers may be aware of common misconceptions about adaptation and may already discuss them with their students, many teachers may not be aware of them or may have misconceptions themselves (Yates & Marek, 2013). If common misconceptions about adaptation and natural selection were addressed and in the curriculum documents, teachers would be more likely to address misconceptions in the classroom.

5.6.2 Recommendations for teachers

While the curriculum is the foundation from which teachers and textbook authors take their cue, teachers are responsible for communicating and encouraging students to develop knowledge about certain topics. If teachers are aware of problems in the curriculum documents or in textbooks then they can correct them and help students develop accurate scientific ideas. One way of reaching teachers in South Africa is through workshops run for regional cluster leaders around the country. The cluster leaders would then be tasked with filtering the information down to teachers in their region. The following recommendations for teachers arise out of this dissertation.

Recommendation 1: teachers could reduce the definition of the concept of adaptation to six essential concepts. The explanation of adaptation in the Grade 8 Natural Sciences curriculum is very broad and most students in this study did not know how to explain it. This research project has shown that students are missing many fundamental concepts essential to understanding the topic of adaptation (see Section 4.2, p. 83). For example, the idea that *adaptation is a process that occurs by natural selection* was missed by 99% of students before instruction; the idea that *adaptation occurs to populations* was not mentioned by a single student before instruction and neither was the idea that *adaptation takes generations to occur.* While students are learning about adaptation in Grade 7, 8, 10 and 11, very few students are learning any adaptation-related content of scientific value. Reducing the broad definition of adaptation to a few key concepts may help teachers and students more accurately explain the topic.

Recommendation 2: when teaching natural selection, Grade 12 teachers should link natural selection back to the topic of adaptation and explain the relationship between the two topics to students. Room for this is made in the Grade 12 Life Sciences curriculum in the explanation of what needs to be taught about natural selection, which says, "pressure leads to extinction or successful adaption (sic)" (Department of Basic Education, 2011b, p. 61). Teachers should seek to explain that natural selection leads to the adaptation of populations over generations, an idea students were introduced to in previous grades. This study has shown that students have a poor understanding of adaptation and natural selection and very few were able to explain that adaptation is the result of the process of natural selection.

Recommendation 3: teachers should familiarize themselves with the 'evolution on demand' alternative framework and its associated misconceptions so as to address or confront these unscientific ideas in class. The most frequent misconceptions in students' responses in this study were all from the 'evolution on demand' alternative framework (see Section 2.4.2, p. 33). Familiarity with the 'evolution on demand' alternative framework and related misconceptions will aid teachers develop teaching strategies that address them so that their students are able to avoid these misconceptions in tests and exams. Pointing out and helping students to correct these misconceptions will improve their ability to communicate their understanding of natural selection and adaptation which will help to improve academic performance.

Recommendation 4: where possible, the use of metaphorical language, like anthropomorphism and teleology, should be avoided when explaining adaptation (Sanders, 2014b). Teleology – the tendency to explain object and events according to their function or purpose – and anthropomorphism – the tendency to attribute human-like thoughts and behaviours to non-human entities – can substantiate unscientific ideas present in students' thinking or cause students to misinterpret the information the teacher is presenting. For example, saying that 'a polar bear developed a fur coat because it needed it in order to survive' may be an easy way to explain the presence of the fur coat. But, it may cause students to think that the polar bear was conscious of its need for the coat, or that its need for the coat contributed to the development of the coat. These ideas omit an explanation of natural selection, the mechanism by which the coat developed. Anthropomorphism and teleology were also commonly used in students' responses to the questions in this study. The use of teleology was particularly pervasive with 77% of the sample making use of teleology in their responses to the pre-instruction instrument (see Section 4.5.1, p. 108). Anthropomorphism was less pervasive, but no less problematic, with 28% of students making use of it in their pre-instruction responses (see Section 4.5.1, p. 108). The use of such language by students may indicate hidden misconceptions, conceptual confusion and an inability to explain adaptation in terms of natural selection. Jungwirth (1975, p. 100) provides an important insight, "Teachers, teacher-educators, science text writers and other relevant persons should be aware of the problem of distorted concepts which might arise from careless/or irresponsible usage of the language of science" (Jungwirth, p. 100).

5.6.3 Recommendations for further research

Recommendation 1: research could be conducted on teachers' understanding of biological adaptation as a possible source of student misconceptions. Research shows that teachers have common misconceptions about evolution (Jiménez Aleixandre, 1994; Yates & Marek, 2014) and that students of teachers with such misconceptions tend to have more misconceptions (Yates & Marek, 2015). Research specifically on teachers' understanding of adaptation is not present in the literature reviewed for this study. Teachers are a possible cause of adaptation-related misconceptions and research into their knowledge of adaptation would provide valuable insight into teachers as a possible cause of misconceptions.

Recommendation 2: research on Grade 12 students' understanding of adaptation-related statements in Grade 12 textbooks. Textbooks have been shown to contain actual errors and latent problems which may be a cause of misconceptions (Sanders & Makotsa, 2016; Tshuma, 2016). While actual errors are a problem, researchers are more concerned about latent problems because they are not easily identified and can be misleading (Tshuma & Sanders, 2015). Research into Grade 8 students understanding of problematically worded statements in textbooks revealed that they can be a cause of misconceptions (Robertson, 2015). The extent to which this is true for Grade 12 students is not yet known.

5.7 CONTRIBUTIONS OF THIS STUDY TO THE FIELD OF EVOLUTION EDUCATION

My study has made five contributions to the literature on evolution education, two of which are novel contributions.

Firstly, *missing concepts in students' explanations* of adaptation has not been reported on in the literature. This project has looked at this at two levels on Bloom's taxonomy of cognitive objectives, comprehension and application. By identifying the concepts that students do not include in their answers, teachers can focus on these essential key concepts in their teaching. These concepts are critically important to a scientific understanding of adaptation.

Secondly, this research project has made an original contribution to the literature on the *nature and extent* of the scientific concepts held by students' about adaptation and natural selection. While some specific concepts have been identified in the literature, this dissertation presents data detailing students' scientific ideas and the extent of their understanding for **each of the concepts** essential for a complete understanding of adaptation and natural selection.

Thirdly, this dissertation adds to the body of knowledge that exists about students' misconceptions about evolutionary topics, specifically adaptation. Few studies internationally focus on students' misconceptions about adaptation and I have not found literature specific to South African students' misconceptions about adaptation. This dissertation identifies the various misconceptions that students battle with and provides data to show the frequency of the misconception in the sample. This research project adds to the already existing body of knowledge internationally, and begins to have a look at the extent of the problem in South Africa.

Fourthly, theoretical discussions about the problem of alternative frameworks can be found in the literature (Jensen & Finley, 1995; Sanders, 2014b; Tshuma & Sanders, 2015), but I have not found data that demonstrates the pervasiveness of alternative frameworks in students' thinking about adaptation in a sample of students. The data provided in the research project helps to establish the extent of the use 'evolution on demand' alternative framework and the 'survival of the fittest' alternative framework in this sample of students, and lays a foundation for other studies, with more representative samples, to demonstrate the extent of the problem nationally.

Finally, this dissertation shows that teleology and anthropomorphism are common in students' explanations of adaptation and that these ways of speaking often substitute for the correct scientific explanation when students cannot provide one or have underlying alternative frameworks. While the discussion on these ways of speaking is contentious in the science education literature, this dissertation demonstrates that teleology and anthropomorphism should not be used in explanations of adaptation because natural selection is replaced as the causal mechanism of adaptation by an organisms need or conscious effort.

5.8 FINAL WORDS

While the topic of *adaptation* in the South African curriculum might be viewed by some as a minor topic of little consequence, the opposite is true, for two reasons. Firstly, the topic of adaptation is important because it is the first evolutionary topic that students meet in the CAPS curriculum in South Africa. Secondly, adaptation is viewed as a “core topic” in biology, one that was essential to Darwin’s explanation of evolution by natural selection (Bock, 1980, p. 217). For the sake of students’ scientific literacy and their development of the “knowledge, skills and values worth learning in the South African Curriculum” (Department of Basic Education, 2011b) it is important that students have an accurate understanding of adaptation, one that reflects the understanding of scientists working in the field of biology. I hope that this research project makes a meaningful contribution to evolution education research and inspires further research on this topic in the future.

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APPENDIX A

Pre-instruction diagnostic activity

Identification Code

DEVELOPMENT OF NEW TRAITS IN LIVING ORGANISMS

1. The pepper moths that lived in England in the 1800’s were generally grey in colour and were well camouflaged on the grey tree trunks. During this period, the industrial activity in England increased the amount of smoke and soot, causing tree bark to become darker in colour. More dark moths then started to appear.

   Explain, as fully as possible, how you think this happened.

2. The large ears of an elephant play an important role in the regulation of an elephant’s body temperature.

   Explain, step-by-step, how elephants developed large ears. You should start your explanation by referring to elephants that had smaller ears in the distant past.

3. From the options below, circle the answer that is the ***most scientifically correct explanation*** for how desert plants have become suited to the environment in which they live.

   e) Plants which grow in hot and dry regions need to survive so try to develop features which enable them to reduce water loss.

   f) Plants which grow in hot and dry regions have features which enable them to reduce water loss.

   g) Plants which grow in hot and dry regions develop features which enable them to reduce water loss.

   h) Plants in hot and dry regions develop features in order to reduce water loss.

   Please explain why you selected that answer.

   ____

   ____

   ____

   ____

How sure are you that your answer is correct?	I am sure ☐	I think so ☐	I am guessing ☐

Identification Code ☐

WHAT HAVE YOU LEARNED ABOUT ADAPTATION AND NATURAL SELECTION?

Have you learnt about adaptation of living things before? Yes ☐ No ☐

If so, in which grade/s? Grade/s _______

Have you learnt about natural selection before? Yes ☐ No ☐

If so, in which grade/s? Grade/s _______

At primary school, did you learn about

- how plants and animals are suited to their habitats, like deserts? Yes ☐ No ☐
- how flowers are modified for insect or wind pollination? Yes ☐ No ☐
- how the respiratory system is modified for gaseous exchange Yes ☐ No ☐

Please explain, as fully as possible, what you understand by the term **‘adaptation’**.

Please explain, as fully as possible, what you understand by the term **‘natural selection’**:

APPENDIX B

Post-instruction diagnostic activity

Identification Code ☐

DEVELOPMENT OF NEW TRAITS IN LIVING ORGANISMS

1. The fruit chafer beetles in South African gardens in the 1980's were generally yellow in colour and were well camouflaged on yellow flowering plants. A drought during this period reduced the number of yellow flowering plants. The fruit chafer beetle found an alternate food source on leafy acacia trees. More emerald (green) chafer beetles started to appear.

   Explain, as fully as possible, how you think this happened.

2. The first seals could only stay under water for short periods before they had to come up to breath. However, today most seals can remain under water for a long time without breathing (nearly 45 minutes). This a big advantage when they hunt for fish deep under the sea.

   Explain, step-by-step, **HOW** modern seals developed the ability to hold their breath for a long time under water (i.e. explain how the change happened). You should start your explanation by referring to ancient seals that could stay under water for only a couple of minutes.

3. From the options below, circle the answer that is the *most scientifically correct explanation* for how camels have become suited to the environment in which they live.

   i) Camels in the hot, dry desert need to survive so try to develop features which enable them survive the hot environment.

   j) Camels in the hot, dry desert have features which enable them to survive the hot environment.

   k) Camels in the hot, dry desert develop features which enable them to survive the hot environment.

   l) Camels in the hot, dry desert develop features in order to survive the hot environment.

   Please explain why you selected that answer.

   ____

   ____

   ____

   ____

   How sure are you that your answer is correct? I am sure ☐ I think so ☐ I am guessing ☐

WHAT HAVE YOU LEARNED ABOUT ADAPTATION AND NATURAL SELECTION?

Please explain, as fully as possible, what you understand by the term **‘adaptation’**.

Please explain, as fully as possible, what you understand by the term **‘natural selection’**:

Please indicate which primary school you completed Grade 7 at:

APPENDIX C

Instructions for the administration of the instrument

The diagnostic activity that follows is designed to form part of the normal teaching and learning process. It is a post-learning assessment activity and should be administered after the section on evolution has been taught. Please keep the following in mind when administering the instrument:

1. The folder marked ‘A’ contains the first part of the diagnostic activity and needs to be handed out first. Please don’t say anything about adaptation, natural selection or evolution prior to this being handed out. This part should take the students between 10 and 15 minutes to complete.
2. Please collect this part of the activity in before handing out the second part of the activity in folder ‘B’.
3. The folder marked ‘B’ contains the second part of the diagnostic activity. You will notice that the words ‘adaptation’ and ‘natural selection’ are used on this instrument, hence the need for this to come after the first instrument.
4. This instrument should take the students about five minutes to complete.
5. Once completed, I would appreciate it if you could place the completed activities back into the folders from which they came and return them to Kerry.

I would like to extend my sincere gratitude to you, once again, for your participation in this research project. Thank you.

Yours in education

Shaun Robertson

APPENDIX D

Example of the coding scheme used to code the natural selection and adaptation explanation questions

Table 34: Coding scheme for adaptation and natural selection

Coding scheme for adaptation and natural selection				
Question students were asked: Please explain, as fully as possible, what you understand by the term **'adaptation'**				
Adaptation is a process by which populations of organisms become better suited to their environment over many generations because of natural selection. An adaptation is also a specific favourable trait that conveys a survival and reproductive advantage over individuals in the population that do not show the trait.				
Points needed to explain biological adaptation				
What biological adaptation is	A1	Adaptation is a process that occurs **by natural selection** **(old A2)**		
	A2	Adaptation works on **populations** of organisms (old A3)		
	A3	They adapt to become more **suited to the environment** **(old A1)**		
	A4	Adaptation occurs **over many generations** **(old A4)**		
	A5	An adaptation can also be a specific **advantageous characteristic** (feature/trait/product) (Old A5)		
	A6	Advantageous characteristics convey a **survival and reproductive advantage** on individuals with the trait (old A6)		
	Aprod	Adaptation as a **product**		
	Aproc	Adaptation as a **process**		
Please explain, as fully as possible, what you understand by the term **'natural selection'**:				
Natural selection is a process that works on natural variation in a population. Certain genetically controlled variations are advantageous for survival and therefore organisms that bear them survive longer and have more offspring. The advantageous trait is passed to some offspring in the next generation through the genes (subject to laws of genetics). The proportion of individuals with advantageous traits will increase in the population over ~~successive~~ a number of generations.				
Points needed to explain natural selection				
Step-by-step explanation of how natural selection happens.	C1	Individuals in a population show **variation** (genetic and phenotypic)		
	C2	Certain variations **favour survival of the organism** in its environment		
	C3a	By surviving longer **individuals with advantageous characteristics get to reproduce** so have more offspring		
	C3b	Individuals that lack the advantageous traits are less likely to survive and reproduce fewer offspring		
	C4	The advantageous traits will thus be **passed on to more offspring** in the next generation than less advantageous features		
	C5	The proportion of **advantageous traits increases** in the population		
Also true	Tr1	This is due to nature / occurs naturally/ is a natural process		
	Tr2	Correctly identifies genes / mutations as being involved in the process		
	Tr3	An explanation for the change in species		
Correct	Nproc	Natural selection is a process		
Not correct	Nprod	Defines NS as adaptations		
Common unscientific ideas to adaptation and natural selection				
Misconceptions associated with the **'evolution on demand'** alternative framework	M1	**Environmental changes cause** / result in adaptation		
	M2	Organisms adapt because they **need to** in order **to survive** the changes (adapt or die)		
	M3	This implies conscious awareness of the threat	M3no	If they deny awareness
	M4	Organisms actively initiate **adaptation**		
	M5	**Individuals** adapt		
	M6	This implies that they adapt **in their lifetime**		
	M7	**Acquired traits pass to offspring**		
Misconcepts associated with the **'survival of the fittest'** alternative framework	S1	"Survival of the fittest" means **only the ones with the advantageous traits survive**		
	S2	Individuals with **advantageous traits WILL survive** *(they can still die of hunger/disease/ predation)*		
	S3	Those with **advantageous traits WILL reproduce**		
	S4	Advantageous traits **WILL pass to ALL offspring** [if only implied, add (i) to code]		
	S5	Those with **less advantageous traits die / become extinct** *(NB: not necessarily)*		
	S5a	They die BECAUSE they cannot adapt		
	S6	Eventually **all individuals in a population will have the advantageous trait**		
	S7	Fitness implies **stronger** organisms / genes		
	S8	Fittest refers to **physical fitness** (use this if it is not clear what they mean when they refer to fitness)		
	S9	Only individuals with **advantageous traits interbreed (mate with one another)**		
	S9a	Weaker organisms do not breed		
	S10	Only the strongest survive (only the physically strong)		
	S10a	The genes will be strong / dominant		
Other unscientific ideas (misc general)	MG1	Adaptation involves organisms **developing into different organisms**	MG16	=allopatric speciation. One organism adapts, the other not. Two different species emerge from one.
	MG2	Natural selection is the **passing on of useful traits** to offspring (this is reproduction)	MG17	Implies nature is an **active agent** in change.
	MG3	Adaptation starts and stops when needed or not needed	MG18	The strong live on the weak (predation) /food chain idea / species select what they will eat
	MG4	Features of an organism are specifically designed for that organism	MG19	X **choses the organism**s to be in a certain area
	MG5	Adaptation is the ability to adapt to an area	MG20	Nature **selects the environment** where an organism can live
	MG5a	They die because they cannot adapt	MG20a	When an organism selects where to live, to survive

	MG6	Adaptation: learning to survive in a new place	MG20b	NS improves the environment
	MG7	Adaptations take a long time to occur	MG20c	When a particular species is chosen for some changes
	MG8	Adaptation: when an organism mates with other organisms in the area in order to survive	MG20d	The organism changes the environment
	MG9	Organisms must move to survive.		
	MG9a	Occurs when an organism moves, so needs to change	MG21	Humans select best traits to live in certain habitats.
	MG10	Adaptation is not evolution of the organism, only a development / reproduction.	MG22	X naturally selecting each other due to similar traits
	MG11	Can be a short term change like physical strength	MG23	Simliar to adaptation but only occurs in certain e.g.s
	MG12	Adaptation leads to stronger organisms	MG24	Will already be suited to own environment so need not change
	MG13	An organism develops specific features (in order to survive)	MG25	Species of the same kind settle in the same environment
	MG14	Natural selection is caused by adaptation	MG26	The natural way species are made
	MG15	Two species from the same environment reproduced to form a new species	MG26a	It is caused by existing genes (ignores mutations???)
Red herrings (off track)				
	RHcomp	Common answer is not to do with natural selection, e.g. competition causes natural selection		
Thinking	A	**Anthropomorphic** thinking involves attributing human behaviour and thinking to animals, gods, or objects.		
	T	**Teleological** thinking involves explaining phenomena by the purpose they serve rather than their actual cause.		
	E	**Essentialist** thinking acknowledges that every entity has a set of attributes that is necessary to its identity and function and thus every living thing is separate, stable and unchanging.		
	L	**Lamarckian** thinking involves explaining that **an individual organism evolves** during **its lifetime** through **use and disuse** of features that develop 'more' when they are used more frequently and grow smaller as they are used less. These **characteristics that are acquired** are inherited by offspring.		
What adapts				
What adapts	WHa	animals	WHspec	species
	WHap	animals and plants	WHoff	offspring adapt
	WHorg	organisms	WHsom	Something / an object adapts
	WHl&nl	living and non-living things can adapt	WHh	Humans evolve (used as an example)
Quality of answer				
Whole answer	Off-track	Answer is not relevant to the question		
	Incoherent	The answer is unintelligible - makes no sense		
	Confused	Answer shows student's ideas are muddled (jumbled, parts of it do not make sense)		
	Language	Poor understanding of English makes the answer difficult to understand (poor wording)		
NoA	Did not write an answer			
DNK	Student said they do not know			
=SF	Natural selection is the equivalent of survival of the fittest			

APPENDIX E

Ethical clearance

Wits School of Education

WITS
UNIVERSITY

27 St Andrews Road, Parktown, Johannesburg, 2193 Private Bag 3, Wits 2050, South Africa. Tel: +27 11 717-3064 Fax: +27 11 717-3100 E-mail: enquiries@educ.wits.ac.za Website: www.wits.ac.za

28 July 2016

Student Number: 0616315X

Protocol Number: 2016ECE028M

Dear Shaun Robertson

Application for Ethics Clearance: Master of Science

Thank you very much for your ethics application. The Ethics Committee in Education of the Faculty of Humanities, acting on behalf of the Senate, has considered your application for ethics clearance for your proposal entitled:

Grade 12 students' ideas about biological adaptation before and after the teaching of natural selection

The committee recently met and I am pleased to inform you that **clearance was granted.**

Please use the above protocol number in all correspondence to the relevant research parties (schools, parents, learners etc.) and include it in your research report or project on the title page.

The Protocol Number above should be submitted to the Graduate Studies in Education Committee upon submission of your final research report.

All the best with your research project.

Yours sincerely,

MMabeta

Wits School of Education

011 717-3416

APPENDIX F

Information letter to parents

INFORMATION ABOUT YOUR CHILD GETTING INVOLVED IN A RESEARCH PROJECT

Information sheet for you to keep

Contact Details:

Name: Mr Robertson
Telephone: (011) 943-2682
(school)
Email: shaun.r01@curro.co.za

Dear parent / guardian.

I am a teacher at a school in Johannesburg and I am conducting research at the University of the Witwatersrand to improve my qualifications and become a better teacher.

The purpose of the research:

The research team that I am working with at Wits is looking at students' ideas about particular topics in biology. This research will help teachers to see what their students think before teachers start a new topic, so that they can design suitable lessons for their classes. I am inviting your child to become involved in this research project. Your child's involvement will benefit all future *Life Sciences* students.

What 'being involved' requires your child to do:

In the *Life Sciences* class your child will be answering a diagnostic activity about their existing ideas before and after learning about the topic of natural selection. This will not take more than 30 minutes. **I am asking if I can use your child's answers to one such class activity, for the purpose of my research.** Giving me permission to do this is entirely voluntary, and your child will not be penalized in any way if you do not give me permission. If you agree I will ask you to sign a "consent form" to formalise your agreement.

What else I am promising you:

- If at any stage you do not wish your child to continue with the research they can tell me so, and I will respect your wishes. They will not be penalized if you withdraw your permission for them to be involved.
- I will not name your child or describe their appearance in a way that may identify them when I discuss my results. The coversheet with their name on it will be separated from the diagnostic activity and replaced with a number e.g. *Student #1.* The class list linking your child's name and number will be locked away in a storeroom and on a password-protected computer, so no-one will be able to link their answers to them. I will also not discuss any personal answers with other teachers or students. Answers will therefore be **anonymous** and **confidential.**
- The information gathered will be used in the write up of a Master Degree dissertation and possibly a journal article.

If you wish to discuss any aspect of the research with me at any point please feel free to contact me at school or by email.

Mr S Robertson

APPENDIX G

Prevalence of ‘evolution on demand’ in each students’ answer to each of the pre- and post-instruction diagnostic activity questions

Table 35: Presence of 'evolution on demand' alternative framework in students explanations of adaptation before and after instruction on natural selection (school 1).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
GT01		Yes			Yes		NO							NO
GT02			Yes	Yes	Yes	Yes	YES	Yes		Yes		Yes	Yes	YES
GT03							NO							NO
GT04					Yes	Yes	NO	Yes	Yes	Yes	Yes	Yes	Yes	YES
GT05			Yes	Yes	Yes	Yes	YES		Yes					NO
GT06	Yes				Yes	Yes	NO							NO
GT07	Yes	Yes					NO							NO
GT08	Yes	Yes					NO							NO
GT 09	Yes	Yes			Yes	Yes	YES	Yes	Yes			Yes	Yes	YES
GT10	Yes	Yes	Yes	Yes	Yes	Yes	YES			Yes	Yes			NO
GT11	Yes	Yes	Yes	Yes	Yes	Yes	YES		Yes		Yes	Yes		YES
GT12	Yes	Yes					NO	Yes	Yes					NO
GT13			Yes	Yes	Yes	Yes	YES			Yes	Yes			NO
GT 14	Yes	Yes		Yes	Yes	Yes	YES							NO
GT 15					Yes	Yes	NO	Yes						NO
GT 16	Yes						NO							NO

Table 36: Presence of 'evolution on demand' alternative framework in students responses to the insect scenarios before and after instruction on natural selection (school 1).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
GT01	yes	yes					NO	yes						NO
GT02	yes						NO	yes						NO
GT03	yes		yes		yes		NO	yes		yes				NO
GT04							NO	yes	yes					NO
GT05	yes				yes		NO	yes	yes					NO
GT06	yes				yes		NO	yes					yes	NO
GT07	yes						NO	yes				yes	yes	NO
GT08	yes						NO	yes						NO
GT 09	yes	yes	yes				NO	yes	yes	yes			yes	YES
GT10	yes						NO	yes	yes	yes				NO
GT11	yes	yes					NO	yes	yes					NO
GT12		yes					NO	yes	yes					NO
GT13	yes						NO	yes	yes					NO
GT 14	yes	yes					NO	yes						NO
GT 15	yes						NO	yes						NO
GT 16	yes				yes	yes	NO	yes		yes	yes	yes	yes	YES

Table 37: Presence of ‘evolution on demand’ alternative framework in students responses to the mammal scenarios before and after instruction on natural selection (school 1).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
GT01	yes		yes				NO	yes	yes	yes	yes	yes		YES
GT02	yes						NO							NO
GT03							NO							NO
GT04	yes	yes	yes	yes	yes	yes	YES	yes			yes			NO
GT05	yes						NO	yes						NO
GT06	yes	yes					NO	yes						NO
GT07	yes		yes				NO							NO
GT08	yes						NO							NO
GT 09							NO	yes	yes	yes				NO
GT10	yes	yes		yes			YES		yes					NO
GT11	yes						NO	yes						NO
GT12	yes						NO							NO
GT13	yes		yes		yes	yes	YES			yes				NO
GT 14		yes			yes	yes	NO							NO
GT 15	yes						NO			yes	yes	yes	yes	YES
GT 16	yes	yes	yes				NO		yes					NO

*NO - undefined

Table 38: Presence of ‘evolution on demand’ alternative framework in students explanations of adaptation before and after instruction on natural selection (school 2).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
WSV1		yes					NO	yes		yes	yes	yes	yes	YES
WSV2		yes	yes	yes	yes	yes	YES							NO
WSV3			yes	yes	yes	yes	YES	yes	yes			yes	yes	YES
WSV4							NO	yes	yes			yes	yes	NO
WSV5		yes	yes	yes	yes	yes	YES		yes			yes	yes	NO
WSV6	yes	yes	yes	yes	yes	yes	YES					yes	yes	NO
WSV7		yes			yes		NO	yes		yes	yes	yes	yes	YES
WSV8		yes	yes	yes	yes	yes	YES	yes	yes	yes	yes	yes	yes	YES
WSV9		yes	yes	yes	yes	yes	YES	yes				yes	yes	NO
WSV10		yes	yes	yes	yes	yes	YES							NO
WSV11		yes	yes	yes	yes	yes	YES					yes	yes	NO
WSV12			yes	yes	yes	yes	YES	yes		yes	yes			NO
WSV13			yes	yes	yes	yes	YES		yes					NO
WSV14	yes	yes	yes	yes	yes	yes	YES					yes		NO
WSV15		yes			yes	yes	NO		yes			yes	yes	NO
WSV16		yes			yes	yes	NO		yes	yes	yes			YES
WSV17			yes	yes	yes	yes	YES			yes	yes	yes	yes	YES
WSV18		yes					NO	yes	yes			yes	yes	YES
WSV19		yes					NO					yes	yes	NO
WSV20				yes	yes	yes	NO		yes	yes	yes			NO
WSV21		yes					NO	yes	yes	yes	yes	yes		YES
WSV22		yes					NO	yes	yes			yes	yes	YES
WSV23		yes	yes	yes			NO							NO
WSV24	yes	yes					NO		yes			yes	yes	NO
WSV25							NO			yes	yes			NO
WSV26	yes	yes	yes	yes	yes	yes	YES		yes					NO
WSV27			yes	yes	yes	yes	YES		yes					NO
WSV28	yes	yes	yes	yes	yes	yes	YES		yes		yes			NO
WSV29		yes			yes	yes	NO						yes	NO
WSV30		yes					NO	yes	yes			yes	yes	YES
WSV31					yes	yes	NO							NO
WSV32	yes	yes	yes	yes	yes	yes	YES	yes	yes					NO
WSV33					yes	yes	NO		yes					NO
WSV34		yes	yes	yes	yes	yes	YES							NO

Table 39: Presence of 'evolution on demand' alternative framework in students insect scenario responses before and after instruction on natural selection (school 2).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
WSV1							NO	yes	yes	yes		yes	yes	YES
WSV2	yes						NO	yes	yes	yes	yes			YES
WSV3	yes	yes	yes		yes	yes	YES	yes						NO
WSV4	yes		yes	yes	yes	yes	YES							NO
WSV5	yes						NO	yes		yes	yes	yes	yes	YES
WSV6	yes	yes			yes	yes	YES	yes						NO
WSV7	yes						NO	yes	yes				yes	NO
WSV8							NO	yes	yes					NO
WSV9	yes	yes					NO	yes	yes					NO
WSV10	yes	yes					NO			yes			yes	NO
WSV11	yes		yes		yes	yes	YES	yes	yes					NO
WSV12							NO	yes	yes					NO
WSV13	yes						NO	yes				yes	yes	NO
WSV14	yes	yes					NO		yes					NO
WSV15	yes			yes	yes	yes	YES	yes						NO
WSV16	yes	yes				yes	NO	yes	yes	yes	yes			YES
WSV17	yes		yes	yes	yes	yes	YES	yes	yes	yes		yes	yes	YES
WSV18	yes						NO							NO
WSVy19	yes	yes					NO							NO
WSV20							NO	yes		yes	yes	yes	yes	YES
WSV21	yes						NO	yes	yes					NO
WSV22	yes	yes					NO	yes	yes				yes	NO
WSV23	yes	yes					NO	yes	yes					NO
WSV24	yes						NO	yes	yes		yes	yes	yes	YES
WSV25							NO	yes						NO
WSV26							NO	yes						NO
WSV27	yes	yes	yes	yes	yes	yes	YES							NO
WSV28	yes	yes	yes				NO	yes	yes					NO
WSV29	yes						NO							NO
WSV30	yes	yes					NO	yes	yes				yes	NO
WSV31							NO							NO
WSV32	yes	yes	yes			yes	YES	yes	yes		yes			YES
WSV33							NO							NO
WSV34	yes						NO							NO

Table 40: Presence of 'evolution on demand' alternative framework in students mammal scenario responses before and after instruction on natural selection (school 2).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
WSV1	yes						NO					yes	yes	NO
WSV2	yes	yes	yes		yes	yes	YES	yes	yes					NO
WSV3	yes						NO	yes						NO
WSV4	yes						NO	yes	yes					NO
WSV5		yes				yes	NO	yes						NO
WSV6		yes					NO							NO
WSV7	yes						NO	yes						NO
WSV8							NO	yes	yes					NO
WSV9	yes						NO	yes						NO
WSV10	yes	yes	yes	yes	yes	yes	YES	yes	yes					NO
WSV11	yes	yes					NO	yes						NO
WSV12	yes						NO							NO
WSV13		yes					NO			yes				NO
WSV14	yes	yes					NO							NO
WSV15		yes					NO	yes	yes				yes	NO
WSV16	yes	yes					NO	yes	yes					NO
WSV17	yes						NO							NO
WSV18	yes						NO		yes					NO
WSV19	yes	yes					NO							NO
WSV20	yes	yes					NO	yes	yes	yes	yes	yes	yes	YES
WSV21	yes	yes					NO	yes	yes					NO
WSV22	yes						NO	yes	yes					NO
WSV23	yes	yes			yes	yes	YES	yes	yes			yes	yes	YES
WSV24	yes		yes	yes	yes		YES	yes	yes					NO
WSV25	yes	yes			yes	yes	YES	yes	yes	yes	yes			YES
WSV26							NO	yes						NO
WSV27	yes		yes				NO							NO
WSV28	yes	yes					NO	yes	yes					NO
WSV29							NO							NO
WSV30	yes	yes					NO	yes		yes	yes	yes	yes	YES
WSV31							NO					yes	yes	NO
WSV32		yes					NO	yes	yes	yes	yes			YES
WSV33							NO		yes					NO
WSV34	yes		yes				NO	yes						NO

Table 41: Presence of 'evolution on demand' alternative framework in students explanations of adaptation before and after instruction on natural selection (school 3).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
PD01							NO							NO
PD02		yes	yes	yes	yes	yes	YES		yes			yes		NO
PD03							NO	yes	yes		yes	yes	yes	YES
PD04		yes	yes		yes	yes	YES	yes	yes			yes	yes	YES
PD05							NO							NO
PD08		yes	yes		yes	yes	YES							NO
PD10	yes		yes	yes	yes	yes	YES		yes					NO
PD11		yes			yes	yes	NO		yes					NO
PD13	yes	yes	yes		yes	yes	YES	yes	yes	yes				NO
PD17	yes	yes	yes		yes	yes	YES		yes	yes	yes	yes	yes	YES
PD19		yes					NO			yes	yes	yes	yes	YES
PD20					yes	yes	NO		yes			yes	yes	NO
PD21		yes			yes	yes	NO		yes			yes	yes	NO
PW22		yes					NO							NO
PW23		yes					NO		yes			yes	yes	NO
PW24		yes			yes	yes	NO		yes	yes	yes	yes	yes	YES
PW26		yes			yes	yes	NO		yes	yes	yes			YES
PW27	yes				yes		NO		yes	yes	yes	yes	yes	YES
PW28	yes	yes	yes	yes			YES							NO
PW29			yes	yes	yes	yes	YES		yes	yes	yes	yes	yes	YES
PW30		yes	yes	yes	yes	yes	YES		yes	yes	yes	yes	yes	YES
PW31	yes	yes	yes	yes	yes	yes	YES		yes			yes	yes	NO
PW32		yes	yes	yes			YES	yes	yes				yes	NO
PW33		yes	yes	yes	yes	yes	YES				yes	yes	yes	NO
PW34	yes	yes	yes	yes			YES			yes	yes	yes	yes	YES
PW35					yes		NO		yes					NO
PW36		yes			yes	yes	NO		yes	yes	yes			YES
PW37		yes	yes	yes	yes	yes	YES							NO
PW38		yes	yes	yes		yes	YES		yes	yes	yes	yes	yes	YES
PW39		yes				yes	NO	yes						NO
PW40	yes	yes			yes	yes	NO		yes					NO
PM42	yes	yes			yes	yes	YES	yes	yes		yes			YES
PM43		yes		yes			NO		yes				yes	NO
PM44		yes					NO							NO
PM45		yes	yes	yes		yes	YES		yes				yes	NO
PM47		yes	yes				NO	yes	yes	yes	yes			YES
PM49			yes	yes	yes	yes	YES	yes	yes					NO
PM51		yes					NO	yes	yes	yes	yes			YES
PM52		yes	yes	yes	yes	yes	YES		yes	yes	yes	yes	yes	YES
PM56			yes	yes	yes	yes	YES					yes	yes	NO

Table 42: Presence of 'evolution on demand' alternative framework in students insect scenario responses before and after instruction on natural selection (school 3).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
PD01	yes				yes	yes	NO	yes				yes	yes	NO
PD02	yes					yes	NO	yes	yes	yes	yes	yes	yes	YES
PD03	yes	yes			yes	yes	YES							NO
PD04	yes	yes	yes		yes	yes	YES					yes	yes	NO
PD05	yes	yes					NO	yes						NO
PD08	yes						NO	yes					yes	NO
PD10		yes					NO	yes	yes					NO
PD11					yes	yes	NO					yes	yes	NO
PD13	yes						NO	yes					yes	NO
PD17							NO							NO
PD19					yes		NO	yes						NO
PD20	yes	yes					NO	yes	yes					NO
PD21	yes	yes	yes	yes	yes	yes	YES		yes					NO
PW22							NO		yes					NO
PW23	yes	yes					NO	yes						NO
PW24		yes	yes				NO	yes						NO
PW26	yes	yes	yes				NO	yes						NO
PW27	yes	yes			yes	yes	YES							NO
PW28	yes		yes		yes	yes	YES		yes					NO
PW29	yes						NO	yes						NO
PW30	yes	yes			yes	yes	YES			yes				NO
PW31	yes	yes	yes	yes			YES							NO
PW32	yes		yes	yes	yes	yes	YES	yes		yes				NO
PW33	yes	yes	yes		yes	yes	YES							NO
PW34	yes	yes					NO							NO
PW35							NO							NO
PW36	yes	yes					NO							NO
PW37	yes	yes			yes	yes	YES		yes					NO
PW38	yes		yes		yes	yes	YES							NO
PW39	yes	yes					NO	yes						NO
PW40	yes						NO							NO
PM42	yes						NO	yes						NO
PM43	yes	yes					NO	yes	yes					NO
PM44							NO							NO
PM45	yes						NO							NO
PM47	yes				yes	yes	NO	yes	yes				yes	NO
PM49	yes	yes					NO	yes		yes				NO
PM51	yes						NO	yes						NO
PM52	yes		yes				NO	yes	yes	yes	yes			YES
PM56	yes	yes					NO							NO

Table 43: Presence of ‘evolution on demand’ alternative framework in students mammal scenario responses before and after instruction on natural selection (school 3).

Student	before instruction							after instruction						
	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework	Environment causes adaptation	Need to change in order to survive	Awareness of need to change	Make the change	Happens to individual organisms	Occurs in their lifetime	Likely to have EOD framework
PD01			yes				NO	yes	yes					NO
PD02		yes					NO	yes				yes	yes	NO
PD03							NO	yes	yes	yes	yes	yes	yes	YES
PD04		yes					NO							NO
PD05	yes	yes					NO	yes	yes					NO
PD08					yes		NO	yes						NO
PD10							NO	yes						NO
PD11	yes						NO	yes	yes					NO
PD13							NO							NO
PD17	yes	yes					NO	yes	yes					NO
PD19							NO	yes	yes					NO
PD20	yes						NO	yes	yes					NO
PD21	yes						NO					yes	yes	NO
PW22		yes					NO							NO
PW23	yes	yes					NO							NO
PW24	yes						NO							NO
PW26							NO							NO
PW27		yes	yes				NO							NO
PW28	yes						NO							NO
PW29	yes						NO	yes	yes					NO
PW30	yes	yes					NO							NO
PW31	yes	yes					NO		yes					NO
PW32	yes						NO					yes	yes	NO
PW33			yes				NO		yes					NO
PW34	yes	yes					NO							NO
PW35							NO							NO
PW36							NO							NO
PW37	yes	yes					NO							NO
PW38	yes						NO							NO
PW39	yes						NO	yes		yes	yes	yes	yes	YES
PW40	yes						NO							NO
PM42	yes						NO		yes					NO
PM43	yes						NO	yes	yes			yes	yes	YES
PM44		yes					NO							NO
PM45	yes		yes		yes	yes	YES	yes	yes					NO
PM47	yes						NO		yes					NO
PM49	yes	yes					NO		yes					NO
PM51	yes	yes					NO	yes						NO
PM52	yes	yes					NO			yes		yes	yes	NO
PM56	yes						NO		yes					NO