Construction of a diagnostic instrument to investigate misconceptions in grade 12 students' understanding of evolution

Kah Huat Robin Seoh, Subramaniam Ramanathan, Yin Kiong Hoh
Natural Sciences and Science Education, National Institute of Education, Nanyang Technological University, Singapore

Abstract

Despite the teaching of biological evolution in the classroom for decades, the learning of concepts related to evolution continue to pose difficulties for students, due to their inability to see the relevance of evolution their everyday experiences. In this study, we report the results from questionnaires composed of twelve multiple-choice items derived and modified from the literature in order to determine the prevalence and severity of alternative conceptions related to soft inheritance and use-and-disuse. In the open-ended section after each item, students were also allowed to describe their reasoning behind the answers they chose. The results showed that while both types of alternative conceptions are present in our respondents as reported in other studies, the rate of application of alternative conceptions dipped tremendously when human-based scenarios were adopted as compared to scenarios involving other organisms. This is especially true for the concepts related to soft inheritance. We attribute the differences to familiarity with elements in the items, and a lack of consistency in applying their biological knowledge. The results suggest that learners tend to apply the correct principles of inheritance only for phenomena that constitute part of their everyday experiences, and have implications for how evolution should be taught.

Introduction

Biology education

There has been a recent shift in dominance of research in physical science to research in biological sciences, allowing biology to be regarded as the pinnacle subject in science research (Hurd, 1997, p41). Simultaneously, technological advancements have allowed biological phenomena to be investigated from different perspectives, such as at the molecular, biochemical or biophysical level. In terms of the national goals of education in the sciences, biology is the science subject that is closest to human life and culture. All these point toward an increasing potential for the use of biology for science education.

To fully support the increasing dominance of biology at the scientific and technological frontier, the A' level biology syllabus in Singapore aims to allow grade eleven and twelve students to consider the explosion in knowledge in Life Sciences, taking into account new and emerging fields in biology; the syllabus integrates, refines and updates the fundamental concepts in biology into structures accessible to all, in order to prepare them for a technologically driven economy in future. From grade one to six, students are taught how life works at the systems level. When they are at grade seven to ten, they learn how life works at the physiological level. At grades eleven and twelve, they start to explore life at the cellular and molecular levels, and are encouraged to balance their understanding of biology with the study of diversity and evolution.

By including evolution as a core topic to be emphasized only from grade eleven onwards, planners of the curriculum are testifying tor the importance of the topic for the comprehensive understanding of biological topics, as well as acknowledging that only sufficiently mature students are capable of understanding evolution well. For the few topics in biology in which student conceptions and alternative conceptions (ACs) have been explored, evolution is amongst the best studied, and yet the one in which educators continue to have the most difficulties in teaching despite various recommendations from the literature, which is a testament to how students' prior conceptions are incompatible with concepts in evolution.

It is essential that evolution is taught well to students, and that ACs are addressed as far as possible. Regarded by many biology educators as a cornerstone concept in biology (Stern, 2004; Ferrari & Chi, 1998; Martin-Hansen, 2008), the concept of evolution explains the unifying features and diversity displayed within and between living organisms. It has increasingly been included as part of current K-12 science curricula worldwide, and is regarded as "fundamental to the training of biologists" (McGlynn, 2008). The importance of the topic in building the fundamentals to understand and appreciate various other topics in biology has therefore resulted in an increase in efforts to teach evolution (Alters & Nelson, 2002).

Background and Rationale for the Study

Alternative Conceptions

Misconceptions are commonly given various names, such as pre-conceived ideas (Johansson, Marton & Svensson, 1985), alternative frameworks (Gilbert & Watts, 1983), naïve conceptions (Champagne, Gunstone & Klopfer, 1983) and alternative conceptions (Wandersee, Mintzes & Novak, 1993). These are the views of learners that differ from the scientifically accurate conceptions held by scientists (Wandersee, *et al.*, 1993), which are logical (but scientifically unacceptable) explanations that learners develop to understand phenomena of the natural world (Blosser, 1987). We shall use the term alternative conceptions (ACs) in this paper – after all, the students need to be given some credit for being able to formulate a conception (Driver, 1981).

ACs are to be distinguished from other types of errors such as a slip of tongue, or information processing errors, both of which are relatively easily taught or corrected (Fisher & Moody, 2001). ACs occur frequently in classrooms worldwide, and are surprisingly resistant to change, especially when traditional or didactic teaching approaches were adopted (Fisher & Moody, 2001). The resistance to change is believed to stem from the resilient network of concepts in the mind of the learner (Chinn & Brewer, 1993). In order to clarify the reasons for the resistance, it might be useful to investigate how a learner analyses and internalizes information about the laws of nature (Johansson, Marton and Stevenson, 1985).

The two types of ACs examined in this paper could have stemmed from the tendency of learners to ascribe a sense of agency or goal-directed nature to natural phenomena like evolution (Resnick, 1994), which could have arisen from the use of figurative language in science and science education (Moore, *et al.*, 2002). Such intellectual shorthand descriptions may serve to foster student misconceptions (Moore, *et al.*, 2002), and worldviews generated from sources such as science fiction may also further embed these misunderstandings, despite the potential for the use of science fiction in countering ACs in evolution (Bixler, 2007). The result is that students might confuse micro-level types of causality and macro-level types (Chi, 2005). Educational emphases on microevolutionary processes may also lead to a poor understanding of macroevolution and speciation processes in teachers and students (Catley, 2006), and the same situation can also be observed in the A' level syllabus in Singapore, where most of the topics taught placed a focus on micro- and microevolutionary processes, with macroevolutionary concepts taught disparate from the other topics such as genetics and cellular mechanisms. Such a focus has been thought to result in evolution being a very difficult topic for students (White, *et al.*, 2013).

We have also chosen to report only on these two types of ACs (soft inheritance and use-and-disuse) as the number of items for each AC allowed for a somewhat meaningful comparison between scenarios involving humans and those involving animals. This comparison is not always possible for the ACs we tried to characterise. For example, items based on the common ancestry of biological organisms involved both humans and animals, or only certain groups of non-human animals, and those that tested whether students viewed natural selection as a process or as an event typically involved only animals. In our original instruments, we had not really expected the differential application of student conceptions in humans and in animals, and as a result, the items in the original instruments were largely based on non-human animals, and only these two ACs had items that allowed for comparisons between human and non-human based scenarios. The results for the other ACs were used primarily as feedback to create more robust instruments to diagnose if differential application of each type of AC exists.

Soft Inheritance AC

Several types of ACs are prominent in studies on learners' understanding of natural selection leading to evolution, and one of them is where learners believe that an offspring will inherit part (or all) of the traits that its parents have developed in their lifetimes, such as a greater muscle mass (Lawson & Thompson, 1988). This conceptual position tends to be Lamarckian in nature, and proposes that organisms are able to inherit acquired characteristics that their parents accumulate in their lifetimes. ACs regarding the direct inheritance of traits have persisted for at least 2000 years, even during Darwin's time (Gregory, 2009).

ACs associated with soft inheritance are inherently very difficult to correct as they can be misconstrued as an extension of the scientifically accurate inheritance of (genetically determined) traits. One of the fundamental concepts behind natural selection is that individuals tend to be more similar to their parents as compared to other individuals of the population, which in turn allows for them to act as propagators of the respective genes and alleles that they inherited from their parents. However, two distinctions between genetic similarity and simply trait similarity must be made clear to the learner: firstly, only genetic similarity can be inherited via allelic and genetic combinations in the gametes, and traits that were developed over an organism's lifetime do not get transmitted to the offspring via the gametes; the other distinction is that while organisms inherit these genes and alleles from their parents, they are neither purely clones of either parents nor even intermediates in terms of characteristics that represent the averages of either parents – there is an element of chance and probability involved that determines the precise genetic and allelic combinations that individual offspring may inherit, for traits involving both continuous or discontinuous variation. Therefore, genetic and phenotypic resemblance of offspring to parents as described in the literature must be viewed from a broad, statistical point of view. Such distinctions are rarely made apparent in science education. Moreover, learners often have great difficulties understanding concepts related to chance and probabilities (Gregory, 2009), culminating in the prevalence of this AC. For instance, learners might think that somehow there is a feedback between beneficial traits developed over an organism's lifetime, as how these beneficial traits (but not others) will be the only ones that are transmitted to the next generation.

Use-and-disuse AC

Another type of related AC is regarding the use-and-disuse of traits, where the learner erroneously accepts that a sudden gain or loss of specific traits is possible due simply to the ancestral populations' over-usage or lack of usage of specific organs in a manner that does not involve natural selection (Gregory, 2009), although the loss of traits can often be better accounted for by mechanisms that involve natural selection (Espinasa & Espinasa, 2008). In this study, this type of AC is distinguished from those in soft inheritance by involving the redundancy of a trait (or the sudden use of a redundant trait). The AC is based on the understanding that organisms will directly evolve whatever they need and lose traits that no longer serve a function. Although the view was originally espoused and proposed by Jean-Baptiste Lamarck as a pre-Darwinian explanation of evolution, it was also at times adopted by Darwin who attributed the loss of sight in cave-dwelling organisms simply to disuse (Darwin, 1859).

ACs related to needs-based accounts for evolution often comprises a circular logic which is intuitive, self-explanatory and very difficult to counter – organisms evolve what they need, and all that they "need", they have already evolved. According to such logic, organisms do not "need" any other features to survive and reproduce in their current environment, and there is somehow an endogenous process that ensures the survival of species (Shtulman & Calabi, 2013). But a critical analysis of the circular logic reveals a flaw: if a new, genetically-coded trait suddenly arises (perhaps out of mutation or outbreeding) in a population in a way that confers great reproductive success upon one or a few individuals relative to those of others in the population, the conditions for natural selection can be altered drastically and what existed previously as not quite needed might suddenly become very useful in the population. The reverse is true, that the traits previously deemed to be very useful might suddenly appear not quite useful in a new environment or mode of living due to factors

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

beyond the control of the individual. Although such "unneeded" traits might diminish over time, the mechanism by which they diminish is better be explained by natural selection and differential reproductive success of organisms with the trait relative to those without the trait, than by whether the organism needed these traits or whether they opted to reduce the trait. Also, many more species have become extinct as compared to number existing species on Earth, which does not support the notion that species will always survive and become fitter.

The adoption or acceptance of these two types of ACs may allow for a position of the learner that accepts the fundamental understanding that organisms can evolve, but also a distorted view of the mechanisms behind evolution. This works possibly by undermining the role of natural selection and genetics, and overestimating the roles of other concepts such as the effects of training or some other automatic process that somehow ensures the survival of the species in relation to its environment (Shtulman & Calabi, 2013). The conceptual position also erroneously accords natural selection and evolution as a perfect set of mechanism that allows for organisms to be perfectly adapted to the environment they live in, instead of a dynamic view of relative fitness of organisms in conditions that are everchanging, or that offspring at birth will always and can only become better adapted to the environment than its parent was at birth (Shtulman & Calabi, 2013).

Although an acceptance of natural selection is correlated to its accurate understanding in teachers (Rutledge and Mitchell, 2002; Deniz *et al.*, 2008), this correlation appears to be very weak in students (Bishop and Anderson, 1990; Demastes *et al.*, 1995; Brem, *et al.*, 2003; Sinatra, *et al.*, 2003; Ingram and Nelson, 2006; Shtulman, 2006). Regardless of whether learners accept the validity of evolution by natural selection, the understanding of natural selection and its role in evolution is generally found to be very poor. Therefore, there appears a need to characterise and understand these two types of ACs in order to address the fundamental ACs regarding evolution.

Previous research has shown that the types of ACs and rate of ACs articulated by museum visitors differ according to the type of organisms considered (Spiegel, *et al.*, 2006), little research is done on why certain organisms elicit a high degree of ACs or certain types of ACs, and if there are any organisms that do not elicit ACs for specific concepts. We hope to contribute by shedding more light on the criteria for the type(s) of organism considered in different evolutionary scenarios, and the corresponding type or level of ACs we can expect in student responses. The finding might be useful for the consideration of educators when they are planning to teach specific concepts in evolution.

Although there have been many reports of ACs about the various concepts in evolution, each study had adopted different instruments consisting of a highly variable number of items to test different concepts of the topic, which often makes direct comparisons about the severity of each AC rather difficult (Gregory, 2009). The comparison of student conceptions across regions is even more problematic as it has been found that the type of organism that respondents encounter affects the accuracy of their answers (Spiegel, *et al*., 2006). A closer examination of the various instruments used also reveals the inadequacy of most items in understanding student ACs. One possible issue is that some of the items might not be contextualised in local terms for students to comprehend. Another is that some of the items might not be pitched at suitable levels for students at each stage. These issues suggest that universal instruments might not be very helpful in understanding conceptions of local students, and this might be especially pertinent for a topic such as evolution that tends to be text-intensive. Although Evans *et al.* (2010) suggest that problems in the acceptance and understanding of evolution stem not from cultural influences, but rather, to "intuitive reasoning processes that constrain children's grasp of biological phenomena", this still need to be corroborated by studies in different regions of the world. To our knowledge, very few of such studies have been conducted in Asia. As the student population in Singapore comprises very racially and religiously heterogeneous group (predominantly made up of Asians), such a study has the potential to provide more information on the ubiquity and severity of ACs in Asia.

Diagnostic instruments composed of single-tier multiple choice items also do not generally reveal very much about the reasoning of respondents in arriving at a particular response, as simple MCQ items may not allow discrimination between intelligent guesses and correct conceptions. Despite it being a popular and common method of assessment due to the ease of implementation as well as the possibility of automation to achieve savings in time and cost of administration, MCQs can be misleading indicators of students' understanding and knowledge, and students' choices should be interpreted carefully (Dufresne, Leonard, & Gerace, 2002). This is despite the easier implementation of MCQs in which diverse scenarios can be presented to students to elicit their conceptions under different contexts and through the use of different organisms. This allows educators to efficiently manage the data obtained through MCQ tests, and characterise the prevalence of each type of AC of learners. There is thus a need for MCQ tests that can measure quickly and adequately the severity and range of local ACs, along with the reasoning patterns behind them, so that educators can efficiently diagnose the types of ACs for the learners under their charge, and subsequently adopt suitable strategies to help them overcome these ACs. In this study, we hope to make use of a diagnostic test composed primarily of MCQ items with spaces for students to elaborate on their understanding, so that the written responses of respondents could be further analysed if required to characterise the nature of their conceptions.

Research Question(s)

Specific research questions are as follows. What is the prevalence of ACs regarding soft inheritance and use-and-disuse scenarios for Grade 12 students? Is there a difference in the rate of application of ACs for soft inheritance and for use-and-disuse scenarios? How do student conceptions for human-based scenarios differ for scenarios involving other non-human organisms? How do the prevalence of ACs in soft inheritance and use-and-disuse scenarios compare with those obtained in other similar studies? How do student descriptions for each item support the option they chose for each item?

Methods

Respondents

A total of 192 Biology students from two junior colleges in Singapore were surveyed. The student population is heterogeneous and expected to be similar to the makeup of the population at large, which is predominantly made up of Chinese, but also with significant numbers of Malays, Indians and other races. In terms of the religious makeup, a majority is expected to be Buddhists, Taoists and Christians, with a significant proportion of Muslims and Hindus as well. Racial and religious data was not collected from the student population as these were regarded sensitive information. In general, the population can be regarded as a heterogeneous Asian society made up of a majority of Chinese. These students from each school were randomly assigned to complete either questionnaire A (n=106) or B (n=84). About 34.9% (n=67) of the sample group were males, and 61.5% (n=118) were females (numbers do not total up to 100% as a few did not indicate their gender). The students were aged around 17 to 18, and were grade 12 equivalent. They had completed formal lessons on the topic of evolution, and had been instructed on the principles of inheritance and the concept of natural selection leading to evolution.

Conceptual Questionnaires

Two conceptual questionnaires were created based on items modified from other instruments in the literature (Brumby, 1979; Lawson & Thompson, 1988; Amir & Tamir, 1994; Jeffery & Roach, 1994; Ferrari & Chi, 1998; Anderson, Fisher, & Norman, 2002; Shtulman, 2006; Deniz, *et al.*, 2008; Nehm & Schonfeld, 2008; Gregory, 2009; Anderson, Fisher, & Norman, 2010; Nehm & Schonfeld, 2010; Andrews, *et al.*, 2012), as well as questions from the A-level examinations. The two questionnaires originally composed of 24 MCQ items each and 1 open-ended question, but only the results for 12 items crafted to measure ACs in soft inheritance and use-and-disuse were reported in this paper.

Each item comprises of a stem that provides the context for the item, accompanied by typically three to five choices that respondents could opt for. A blank option is provided for every item as well to allow respondents to pen down alternative answers if the options provided did not match their understanding well. In addition, for each item, respondents were also asked to describe or explain the reasons for their chosen multiple choice response(s).

A sample item each for soft inheritance and use-and-disuse is provided below for reference:

Item A10: A population of lab mice develops stronger muscles and becomes hyperactive after being put on a protein-rich diet. Based on the concepts of natural selection, if ten generations of mice were fed the high-protein food, what should happen to the descendants of this population of mice as compared to the first generation of mice who were fed the high protein food?

A. They should become stronger and hyperactive from birth as compared to the first generation.
B. They should become stronger but not hyperactive from birth as compared to the first generation.
C. They should be just as strong, but hyperactive from birth as compared to the first generation.
D. They should have the same physical characteristics as the first generation.
E. Other answers: ________________________________ ( )

Reason for my answer:

____

____

Item B5: The wing feathers of some crows were clipped, rendering them unable to fly. The wing feathers of the offspring of these birds are also clipped. This was repeated for many generations. Compared to the offspring of other crows, the descendants of those with clipped wings should have which of the following features?

A. Shorter wing feathers
B. Longer wing feathers
C. Either shorter wing feathers or longer wing feathers
D. Other answers: ________________________________ ( )

Reason for my answer:

____

____

Data Analysis

The multiple choice responses and the written reasons for the responses were then transferred into an excel file for analysis. The frequencies of scientifically acceptable responses, as well as the frequencies of responses that indicated the presence of alternative conceptions were tabulated for each item. The results were then grouped into ACs related to soft inheritance and use-and-disuse, and further sub-grouped into humans as compared to non-human organisms. The written responses were read carefully to understand the reasoning behind students' responses and alternative conceptions.

Results

ACs Associated with Soft Inheritance

Table 1 shows the summary of results for students' answers to the items that tested for the ACs related to soft inheritance, in which students accept that acquired characteristics in the lifetime of an organism can be directly inherited by the offspring of the organism. Such conceptions typically do not provide due considerations to how character traits are inherited via the genes of the organism that are passed from generation to generation and within gametes.

The results show that when human scenarios are provided, there is a very low incidence for the adoption of responses related to soft inheritance. Items A9, B9, B10 and B11 are such items. The total incidence of students opting for responses other than the ones demonstrating acceptable conceptions is consistently low for these items (less than 15%), and the proportion of responses deemed scientifically acceptable ranged from 85.9% to 96.5%. The frequency of opting for specific options related to alternative conceptions was also very low, with the highest at 6.7% (where students indicated that a person's natural hair colour which was originally fair might be altered to black after years of dyeing the hair black). For the item B10, very few written responses were given by the respondents, and the written responses provided did not specifically relate to any known ACs.

However, when the stem involved animals, the frequency of ACs increased greatly. Many students accepted that food sources (as described in item A10 and A17) and characteristics acquired by training (as described in items A11 and A12) have the potential to change the character traits and behaviour of the offspring of organisms directly. In some cases, students opted for the responses indicating that the need for the trait or the need for survival caused those changes. The frequency of the ACs related to soft inheritance was deemed to be very high when non-human organisms were used, and it ranged from about a quarter of all respondents to approximately two-thirds. It is interesting to note that for question B8, which involved cheetahs and natural selection for speed (a familiar scenario for students), the incidence of ACs is relatively low compared to other less familiar scenarios involving non-humans, but still high when compared to scenarios involving humans.

Some of the reasons students gave to support their AC-related responses are highlighted in Table 1, and the descriptions underscore the presence and prevalence of ACs associated with soft inheritance, which disregards the principles of genetics and inheritance, even though these topics have already been taught to them. Nonetheless, the fact that respondents were better able to apply the correct principles in the analysis of human-based scenarios or for more familiar scenarios as compared to less familiar, animal-based scenarios, suggests that most of them understood these scientific principles, but only adopted them in the more familiar scenarios, and this resulted in the selective expression of the AC.

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

Table 1

Summary of Results for Items Based on Soft Inheritance ACs

Item	Description	Frequency of Acceptable Conceptions	Frequency of Alternative Conceptions	Student Reasoning Demonstrating Alternative Conceptions
A9	Dyeing of Human Hair	89.5	6.7 (hair dye affects an individual's phenotype directly over time)	"The girl's hair is subjected to the additive effect of the environment (where she chooses to dye her hair constantly)."
B9	Tanning of Human Skin	85.9	5.9 (environment can change genotype) 4.7 (others)	"Mutation of the melanin gene are passed down to the children."
B10	Human Finger Amputation	96.5	N.A.	No AC described in student answers.
B11	Human Muscle	87.1	9.4 (direct inheritance of acquired traits)	"Amplification of the gene which resulted in increased protein production."
A10	Mice Feed	36.4	44.9 (diet affects offspring trait and behaviour directly) 10.3 (diet affects offspring behaviour directly)	"It is similar to the evolution of human brain which tells that human brain becomes bigger and more developed since humans started eating fish / meat." "The stronger trait will be passed down to offspring." "The muscles will be put to good use as the mice adapts to the presence of them."
A11	Finches' Wing Muscles	32.7	38.5 (direct inheritance of acquired traits) 10.6 (others)	"Natural selection selects those that have stronger wing muscles, thus only those who have stronger wing muscles will survive." "…Due to parents developing stronger wing muscles, consequent offspring are born with the trait only, since there is a geographical barrier which inhibits gene flow into the island."
A17	Birds' beak length	35.2	54.3 (environment directly allows trait changes)	"They need a larger beak to eat the food." "The need to feed on the insets for survival will develop longer beak foe the offspring."
B8	Cheetahs' Evolution of Speed	74.1	12.9 (direct inheritance of acquired traits) 11.8 (needs drive change)	"Cheetahs are born fast so that they can catch their preys, thus they pass down the desirable traits." "Must be fast in order to catch preys and have food for survival." "The fact that they can acquire the trait and pass it on to offspring, allows successive generation to slowly but surely increase its speed."

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

ACs associated with Use-and-disuse

The incidence of ACs observed in the scenarios involving use-and-disuse was more consistent than those involving soft inheritance, regardless of whether the stem involved humans or other familiar scenarios. The proportion of responses based on scientific views of evolution was seen to be low in all the questions (see Table 2). Items B6, A6 and A7 were based on traits that might have been products of natural selection, but which were no longer useful in the environment that the organism lives in. Instead of opting for variational descriptions for how the trait might change over many generations as a result of a proportion of individuals having a higher reproductive success than others, the descriptions of a large proportion of respondents demonstrated an understanding that traits that were no longer useful will not be selected for and thus would quickly fade away in subsequent generations (item B6). For example, in item A6, respondents further speculated that the needs of the bacteria can drive evolutionary change (21.2%), or that bacteria lose their antibiotic resistance over generations because they had to survive (11.5%), as compared to the principles of natural selection that evolutionary change is a result of variation within populations and differing reproductive success of different variations, inferring that most of the bacteria might not survive to reproduce.

In item A7, a vast majority of respondents speculated that the size and function of eyes of a fish will undergo evolutionary change over several generations to become bigger (26.5%), smaller (29.5%) or non-functional (34.6%) solely due to the environment, and only a very surprisingly small minority opted for the scientific conception that the eyes would most likely remain about the same size (6.5%), as the fish is bred under well-lit conditions and the size of eyes or whether the fish was vision-capable does not seem to affect reproductive success. There was a great difficulty in vSimilar results were seen in item B7, where only 22.2% opted for the answer most acceptable to scientists that the clipping of the feathers of flight-capable birds would not result in the change in the length of feathers of their offspring. The AC-containing option was chosen by a majority (45.6%) of the students. Analysis of the remaining major group of 25.9% that chose "other answers" revealed that most of this group adopted scientific conceptions and were providing reasons for the wing feathers of offspring to remain unchanged in length, resulting in an approximate frequency of 48.1% that adopted scientific conceptions.

For the only human-based item B5, similar results to non-human items were obtained. Although the majority (44.6%) of respondents chose the option that if a human population switched to a vegetarian diet, there should not be any significant changes in the size and function of their appendix in 100 years, 28.9% selected the responses that suggested the increase in size and restoration of the ancestral function of the appendix, while 18.1% selected the response that suggested that the original function of the appendix might be restored although there might not be a change in the size of the vestigial organ. A detailed analysis of the reasons for ACs reveals the presence of ACs that treat organ / organismal adaptations as selective adaptations. Some responses focused on how needs are sufficient to drive evolution. Although a few responses might be partially right in the application of the principle of natural selection, that people with larger appendix might indeed survive better and reproduce more if a whole population was forced to switch to a vegetarian diet, it is still rather radical to accept that significant changes in the size and function of the appendix might be observed in a few generations (within 100 years).

In all, the frequency of opting for scientifically acceptable answers ranged from 6.5% to 56.6%. The prevalence of ACs related to use-and-disuse appeared to be more prevalent and deeply embedded as compared to ACs related to soft inheritance.

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

Table 2

Summary of Results for Items Based on Use-and-disuse ACs

Item	Description	Frequency of Acceptable Conceptions	Frequency of Alternative Conceptions	Student Reasoning Demonstrating Alternative Conceptions
B6	Lizard Horn Change Over Time	56.6	31.3 (loss of traits that have no known function)	"No use hence it will tend to disintegrate." "As the horn has no obvious function, it will become shorter in length as the body will recognise that the structure is obsolete and thus will not waste much resource on it."
A6	Loss of Antibiotics Resistance in Bacteria	50.0	11.5 (survival driven) 21.2 (needs driven) 14.4 (others)	"… they will not waste nutrient producing resistance gene, thus they will survive better, to give birth and increase population without DDT resistance." "Not required, trait becomes redundant, like the tail in humans." "Don't have to waste resources transcribing and translating for useless proteins."
A7	Fish Kept in Darkness	6.5	34.6 (drop in function) 29.9 (drop in function and size) 26.2 (compensation mechanism that is inheritable)	"There is a lesser need for their eyes to capture light. Hence, their eyes become like the eyes of the blind cave fish." "In near-complete darkness, eyes are not very important." "They need to see. Thus bigger eyes absorb more light so as to see better."
B7	Bird Wing Clipping	22.2	45.7 (clipping offspring feather length) 25.9 (others)	"The crows will slowly stop 'waiting' to fly and thus, have no usage for the wings that they initially have. Over time, the wings will have shorter feathers." "There would not be a use for the feathers therefore the absence."
B5	Human Appendix Change for Vegetarian Diet	44.6	28.9 (diet affects offspring vestigial organ size and function directly) 18.1 (diet affects offspring vestigial organ function)	"Appendix would grow in size to be active in digesting cellulose" "…the appendix will be useful to digest cellulose. People with larger appendix survive better and pass down the genes to their offsprings." "…if descendants switch to vegetarian diet, it will be needed for cellulose digestion." "Vegetables contain large amount of cellulose, the appendix will slowly adapt to digesting cellulose when consumed."

Discussion

Our results suggest that ACs related to soft inheritance and use-and-disuse has the potential to hinder the understanding of evolution based on scientifically acceptable views. The proportion of learners affected is highly variable depending on the scenario presented, but generally, the high frequency of ACs encountered in most of the questions crafted is a cause for worry. For the items related to the soft inheritance AC, we observed that respondents tend to incur lower rates of ACs if human examples were adopted, as compared to non-human examples. There are several possible reasons for the discrepancy. It is possible that students elicit concepts related to the principles of inheritance only when human-based scenarios (or other very familiar scenarios) were analyzed. The A' level syllabus of these students places a very strong emphasis on life sciences, particularly in aspects related to humans, and it is possible that the respondents might not be used to applying the principles of inheritance similarly for non-human organisms. Another related explanation is that respondents might simply not have understood the concept of variation between individuals in animal populations to be able to apply the principles of inheritance appropriately (Shtulman & Calabi, 2013). They could have adopted simplistic or naïve conceptions when attempting to understand non-human scenarios, but adhered more closely to scientific concepts when analyzing scenarios involving humans (or large mammals).

There might have been a greater overall incidence of the adoption of ACs for the use-and-disuse scenarios as respondents might not be as familiar with use-and-disuse scenarios as compared to those based on soft inheritance. Use-and-disuse scenarios might indeed involve a longer time frame and broader scope. For example, soft inheritance scenarios are typically based on variation within in a small family, or how incremental change may occur for a selected trait in a small, isolated population over a small number of generations. However, use-and-disuse scenarios typically require the visualization of the different possibilities in a population when a previously useful feature suddenly becomes redundant or when a vestigial structure suddenly becomes useful, involving many generations and perhaps even the concept of speciation. It is thus likely that there is a greater range of possible answers for use-and-disuse scenarios, resulting in our observations in this study.

In considering how previously useful traits change when they were made redundant, use-and-disuse scenarios might present a conflict with what students are taught in evolution regarding "survival of the fittest", or how organisms' traits make them perfectly suited to live in a particular environment. If a trait renders an organism to be less than "the fittest" in relation to the environment, some respondents might have prematurely and erroneously concluded that the restoration of the "fittest" condition might somehow emerge quickly (Shtulman & Calabi, 2012). This idealistic portrayal of natural selection somehow being a perfect and efficient selecting mechanism contrasts with the scientific concept of natural selection, that chance or probabilistic events such as mutation, independent assortment of chromosomes, catastrophes, and isolating incidents are just as important in causing evolutionary change over time. The confusion between chance or probabilistic events, and processes that are generally directed (such as natural or sexual selection), may act as a breeding ground for such unintentionally generated ACs (Andrews, *et al.*, 2012), and result in learners treating natural selection as a direct process rather than an emergent one. In all, we note that due to these reasons, ACs related to use-and-disuse might be more robust and present greater challenges to educators than those related to soft inheritance.

In this study, the principles of inheritance and the importance of variation in populations were largely downplayed by respondents, and a large proportion of them used organismal needs and "desires", as well as environmental needs to explain evolutionary change. It was reported previously that students might try to learn evolution as a topic separate from other topic when evolution is directly related to many other fields of biology (Alters & Nelson, 2002). A related pattern might be observed here, where the learner segregates the application of the principles of natural selection and evolution from other topics, especially when non-human scenarios were considered. This study highlights that some students may only apply the concepts of inheritance when analyzing scenarios of soft inheritance in humans, but will opt for alternative explanations when non-human scenarios are provided. The inconsistency in the application of this AC suggests that it might also be more resistant to change (Shtulman & Calabi, 2013), and more work needs to be done to examine the effects of instruction on the rate of application of ACs. Also, we found that many students generally did not apply the concept of natural selection when analyzing use-and-disuse scenarios, regardless of whether human or non-human scenarios were provided. Interestingly, the higher rate of consistency in the application of this AC suggests a lower resistance to change, which should be verified.

Implications for Teaching and Learning

Our study has provided a better understanding of the nature of student ACs, and perhaps a glimpse of how the bleak problem of the misunderstanding of evolution can be approached. In terms of the teaching of biological evolution, it might be imperative to continue to emphasise to students that similar principles or rules of inheritance apply for humans as well as other non-human organisms, especially diploid ones, in order to encourage adherence of application for problems involving genetics and inheritance, which students are already aware of (Kalinowski, Leonard, & Andrews, 2010). Careful attention should subsequently be paid to link modern genetics to evolution, specifically that these mechanisms and principles are conserved in human populations as well as in non-human populations. For example, it is necessary for students to internalize that based on the understanding that organisms inherit existing alleles from parents randomly, variations exist between every population for most traits, even when these variations might not be immediately apparent to the untrained student observer. Such variations are inherent in populations (such as the speed of cheetahs or the height of giraffes), and can be observed even within a single brood of offspring. Typically, the trait for the offspring should vary around a mean for which the parents are genetically programmed to carry, and this genetic programming has very little to do with the traits that parents develop in their lifetimes. Such understanding can be derived or enhanced for example by providing more opportunities for learners to observe variation individuals in a natural population, despite their similarities as compared to another population of similar organisms.

Since students tend to encounter a lower level of ACs for scenarios involving soft inheritance in humans as shown in this study, educators could begin by demonstrating the examples of inheritance in humans, before providing parallel (and highly comparable) scenarios in other organisms involving genes-to-selectable-phenotypes as suggested by White, Heidemann, & Smith (2013), for example, by focusing on similar characteristics such as melanin production in humans versus colour production in birds or mice, or other similar scenarios.

Educators should also pay extra heed to highlight to learners the very long time and many generations required usually to cause evolutionary change, as well as the currency of this change (differential reproductive success instead of purely physical or other types of fitness). For example, there is scope for learners to examine closely how evolutionary change takes place over many generations for traits that show discrete variation versus those that show continuous variation. The speed at which evolutionary change takes place can be fast or slow depending on several factors such as the nature of variation and the environmental cause of the selection, but in either case, a stronger emphasis on the mechanisms of natural selection must be clarified such that each variation is not immediately chosen for or selected against; but rather, increases or decreases in frequencies of each variation or allele takes place due to differential reproductive fitness conferred by the allele (or its combination).

Even though respondents encountered a high frequency of ACs involving use-and-disuse scenarios for all organisms, which indicates its high degree of consistency, it is probable that the consistency of this type of ACs also makes it less resistant to change (Shtulman & Calabi, 2013). Therefore, with effective and suitable instruction and intervention measures designed to counter this AC, it is possible that more gains can be made in terms of replacing the ACs with scientifically acceptable conceptions. Educators can teach for optimal learner's gains by applying the inquiry approach to allow learners to analyze such scenarios thoroughly, criticizing or rejecting explanations that do not fit well with the scientifically acceptable conceptions (Robbins & Roy, 2007). Such methods of teaching are the exception rather than the norm currently in the context of Singapore. Based on such methods, it will be useful for learners to examine the conditions for natural selection carefully, to observe clearly whether there were any differences in reproductive success for organisms with different variations of a trait, and the resultant change in allele frequency over subsequent

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

generations. For example, although the clipping of flight feathers of birds over many generations lead to their inability to fly and therefore the disused condition of their wings, the ability to fly is still genetically coded, and the descendants of such isolated populations would still inherit the genes enabling the full development of flight feathers, and thus be able to fly, as long as there is no clear lack of reproductive success against those that were able to fly.

Lastly, we recommend the administration of multiple choice tests based on student ACs, especially the two-tiered multiple choice tests requiring students to explain their choices or select a suitable reason for their chosen answer, so as to understand and address these robust ACs that often escape the attention of the educator (Treagust, 1986; Treagust, 1988). This will provide educators with a clearer profile of the individual learners under their charge, and perhaps allow for their segregation to address specific ACs. With the knowledge gleaned on the severity and nature of each type of AC their charges possess, educators can then proceed to overcome them with tailor-made, effective conceptual change strategies that learners will find meaningful and engaging (Fisher & Moody, 2001).

A Differential Syllabus – An Experiment in Progress?

The differential application of ACs related to soft inheritance, particularly the decrease in applying ACs in scenarios involving humans, serves to highlight one area of success in the education of evolution locally. The decreased application of ACs could be attributed in part to the intensive focus on life sciences, which is heavily based on classical and modern genetics. This success with human-based scenarios is also extended to another familiar scenario involving how cheetahs evolved their fast speed, where approximately three quarters of respondents opted for variational, scientifically acceptable conceptions. A closer analysis of the written responses of students also lends further support to the finding that, by and large, variational approaches were adopted. Our results can be contrasted to those in other studies that reported that only 31% of museum visitors (and therefore the more highly educated strata in the population) in the United States were able to adopt variational explanations for the evolutionary increase in the speed of cheetahs (McFadden, *et al.*, 2007).

It is unclear however, why the relatively accurate level of understanding achieved for soft inheritance in humans was not applied to scenarios involving soft inheritance in birds and mice. It will be both interesting and useful to understand more about the differential rates of application in other organisms, and produce more parallel scenarios to provide more details regarding this discrepancy.

Limitations

Some of the shortcomings in the items of the original questionnaire were addressed in the final instruments as they were re-crafted or edited, but it is probable that some of them (unclear assumptions or unnecessary information) might have increased the frequencies of ACs observed in this study. Also, the scenarios based on humans and non-humans were not made totally parallel in their setting and in the numbers of scenarios provided for comparison purposes, because we had not expected at first the differential application of the principles of natural selection. Moreover, the evolutionary challenges faced by humans appear more complex than those of other organisms due to factors such as complex social systems and culture, which made it difficult to craft parallel scenarios directly. In other words, it is still possible that the contexts of the scenarios, rather than the organisms involved, determine the rate of application of ACs. Lastly, there were difficulties in addressing ethical issues appropriately for human-based scenarios (for example, if manipulation of humans were described) as compared to non-human scenarios. These difficulties had resulted in an uneven number of items, as well as differences in the items, for humans versus non-humans, and care should be taken when comparing the results directly. As mentioned in a previous section, the focus of the A' level syllabus (primarily based on life sciences involving humans) is likely an important factor that makes generalization to respondents in other countries difficult. Some of the issues regarding the preparation of the items were resolved in the final instruments developed from this study.

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

Conclusion

Our study provides a new angle to view student ACs in evolution. It particularly highlights the different degrees of the application of ACs for each type of conception. We have surfaced another possible explanation for why students express different degrees of ACs for different types of ACs surfaces: it is likely to be largely dependent on whether the organism presented to them is one that is familiar to them. The rate of application of scientific conceptions or ACs related to soft inheritance could be dependent on their familiarity to the organism in question (specifically large mammals or humans versus other non-human organisms such as mice, birds or bacteria). Although differences in how museum visitors understand the evolution of different biological organisms has been reported (Spiegel, *et al.*, 2006), this is the first study that demonstrates how students respond starkly differently for evolutionary scenarios involving humans versus non-humans, and specifically for ACs related to soft inheritance but not for ACs involving use-and-disuse.

The discrepancy between the results obtained in soft inheritance and use-and-disuse scenarios with regards to the accurate understanding of human evolution suggests that learners may apply scientifically acceptable conceptions regarding inheritance for some scenarios, but switch to an alternative framework for another scenario. Regardless of whether human or non-human scenarios were considered, the rate of application of ACs related to use-and-disuse is generally very high in our study. The high rate of application of AC for all kinds of organisms suggests that this type of AC is more consistent than that related to soft inheritance, and thus ACs related to use-and-disuse has the potential to be overcome by suitably designed instruction.

It is unclear if the results can be generalizable to students of other countries due to the heavy focus on the life sciences in the A' level syllabus for the respondents in this study. It is probable that the heavy focus on genetics and the principles of inheritance in the A' level syllabus has led to a decrease in the application of ACs related to soft inheritance for scenarios involving humans but not for those involving other organisms. There is a huge potential to harness more information by conducting similar studies elsewhere. For future work, it might also be useful to examine whether our local students treat human and non-human scenarios differently for other types of ACs, such as those relating to essentialism or transformism. Armed with specific knowledge about student ACs, approaches to overcome these specific ACs can then be designed.

References

Abraham-Silver, L., & Kisiel, J. (2008). Comparing visitors' conceptions of evolution: examining understanding outside the United States. *Visitor Studies, 11*(1), 41-54.

Alters, B. J., & Nelson, E. (2002). Perspective: teaching evolution in higher education. *International Journal of Organic Evolution, 56*(10), 1891-1901.

Amir, R., & Tamir, P. (1994). In-depth analysis of misconceptions as a basis for developing research-based remedial instruction: The case for photosynthesis. *The American Biology Teacher, 56*, 94-100.

Anderson, D. L., Fisher, K. M., & Norman, G. J. (2002). Development and evaluation of the conceptual inventory for natural selection. *Journal of Research in Science Teaching, 39*(10), 952-978.

Anderson, D. L., Fisher, K. M., & Smith, M. U. (2010). Support for the CINS as a diagnostic conceptual inventory: Response to Nehm and Schonfeld (2008). *Journal of Research in Science Teaching*, 354-357.

Andrews, T. M., Price, R. M., Mead, L. S., McElhinny, T. L., Thanukos, A., Perez, K. E., et al. (2012). Biology undergraduates' misconceptions about genetic drift. *Life Sciences Education, 11*, 248-259.

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching, 27*(5), 415-427.

Bixler, A. (2007). Teaching evolution with the aid of science fiction. *The American*

Biology Teacher, 69(6), 337-340.

Blosser, P. E. (1987). *Science misconceptions research and some implications for the teaching of science of elementary school students*. Retrieved March 17, 2013, from http://www.ericdigests.org/pre-925/science.htm

Brem, S. K., & Ranney, M. S. (2003). Perceived consequences of evolution: colleges students perceive negative personal and social impact in evolutionary theory. *Science Education, 87*, 181-206.

Brumby, M. N. (1979). Problems in learning the concept of natural selection. *Journal of Biological Education, 13*, 119-122.

Catley, K. M. (2006). Darwin's missing link: a novel paradigm for evolution education. *Science Education, 90*, 767-783.

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1983). Naive knowledge and science learning. *Research in Science and Technological Education, 1*(2), 173-183.

Chi, M. T. (2005). Commonsense conceptions of emergent processes: why some misconceptions are robust. *The Journal of the Learning Sciences, 14*(2), 161-199.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1-49.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life.* London: John Murray.

Demastes, S. S., Settlage, J., & Good, R. (1995). Students' conceptions of natural selection and its role in evolution: cases of replication and comparison. *Journal of Research in Science Teaching, 32*, 535-550.

Deniz, H., Donelly, L. A., & Yilmaz, I. (2008). Exploring the factors related to acceptance of evolutionary theory among Turkish preservice biology teachers: toward a more informative conceptual ecology for biology evolution. *Journal of Research in Science Teaching, 45*, 420-443.

Driver, R. (1981). Pupils' alternative frameworks in science. *European Journal of Science Education, 3*(1), 93-101.

Dufresne, R. J., Leonard, W. J., & Gerace, W. J. (2002). Making sense of students' answers to multiple-choice questions. *Physics Teacher, 40*, 174-180.

Espinasa, M., & Espinasa, L. (2008). Losing sight of regressive evolution. *Evolution Education Outreach, 1*, 509-516.

Evans, E. M., Spiegel, A. N., Gram, W., Frazier, B. N., Tare, M., Thompson, S., et al. (2010). A conceptual guide to museum visitors' understanding of evolution. *Journal of Research in Science Teaching, 47*(3), 326-353.

Ferrari, M., & Chi, M. T. (1998). The nature of naive explanations of natural selection. *International Journal of Science Education, 20*(10), 1231-1256.

Fisher, K. M., & Moody, D. E. (2001). Student misconceptions in biology. In K. M. Fisher, J. H. Wandersee, & D. E. Moody, *Mapping biology knowledge* (pp. 55-75). The Netherlands: Springer.

Gilbert, J. W., & Watts, D. M. (1983). Concepts, conceptions and alternative conceptions:: changing perspectives in science education. *Studies in Science Education, 10*, 61-98.

Gregory, T. R. (2009). Understanding natural selection essential concepts and common misconceptions. *Evolution Education Outreach, 2*, 156-175.

Hurd, P. D. (1997). *Inventing Science Education for the New Millenium.* New York: Teachers College Press.

Ingram, E. L., & Nelson, C. E. (2006). Relationship between achievement and students' acceptance of evolution or creation in an upper-level evolution course. *Journal of Research in Science Teaching, 43*, 7-24.

Jeffery, K. R., & Roach, L. E. (1994). A study of the presence of evolutionary protoconcepts in pre-high textbooks. *Journal of Research in Science Teaching, 31*(5), 507-518.

Jensen, S. M., & Finley, F. N. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Science Education, 79*, 147-166.

Johansson, B., Marton, F., & Svensson, L. (1985). An approach to describing learning as change. In L. West, & A. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 233-258). Orlando FL: Academic Press.

Kalinowski, S. T., Leonard, M. J., & Andrews, T. M. (2010). Nothing in evolution makes sense except in the light of DNA. *Life Sciences Education, 9*, 87-97.

Lawson, A., & Thompson, L. (1988). Formal reasoning ability and misconceptions concerning genetics and natural selection. *Journal of Research in Science Teaching, 25*(9), 733-746.

MacFadden, B. J., Dunckel, B. A., Ellis, S., Dierking, L. D., Abraham-Silver, L., Kisiel, J., et al. (2007). Natural history museum visitors' understanding of evolution. *BioScience, 57*, 875-882.

Martin-Hansen, M. L. (2008). First-year college students' conflict with religion and science. *Science and Education, 17*, 317-357.

McGlynn, T. P. (2008). Natural history education for students heading into the century of biology. *American Biology Teacher, 70*(2), 109-111.

Moore, R., Mitchell, G., Bally, R., Inglis, M., Day, J., & Jacobs, D. (2002). Undergraduates' understanding of evolution:ascriptions of agency as a problem for student learning. *Journal of Biological Education, 36*(2), 65-71.

Nehm, R. H., & Schonfeld, I. S. (2008). Measuring knowledge of natural selection: a comparison of the CINS, on open-response instrument and an oral interview. *Journal of Research in Science Teaching, 45*(10), 1131-1160.

Nehm, R. H., & Schonfeld, I. S. (2010). The future of natural selection knowledge measurement: A reply to Anderson et al (2010). *Journal of Research in Science Teaching, 47*(3), 358-362.

Resnick, M. (1994). Beyond the centralised mindset. *Journal of the Learning Sciences, 5*, 1-22.

Robbins, J. R., & Roy, P. (2007). The natural selection: identifying & correcting non-science student preconceptions through an inquiry-based, critical approach to evolution. *The American Biology Teacher, 69*(8), 460-466.

Rutledge, M. L., & Mitchell, M. A. (2002). High school biology teachers' knowledge structure, acceptance & teaching of evolution. *American Biology Teacher, 64*, 21-27.

Schtulman, A., & Checa, I. (2012). Parent-child conversations about evolution in the context of an interactive museum display. *Internal Electronice Journal of Elementary Education, 5*(1), 47-46.

Shtulman, A. (2006). Qualitative differences between naive and scientific theories of evolution. *Cognitive Psychology, 52*, 170-194.

Shtulman, A., & Calabi, P. (2013). Tuition vs intuition: Effects of instruction on naive theories of evolution. *Merrill-Palmer Quarterly, 59*(2), 141-167.

Sinatra, G. M., Southerland, S. A., McConaughy, F., & Demastes, J. W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching, 40*(5), 510-528.

Yin Kiong Hoh
yinkiong.hoh@nie.edu.sg

Spiegel, A. N., Evans, E. M., Gram, W., & Diamond, J. (2006). Museum visitors' understanding of evolution. *Museum Soc Issues, 1*, 69-89.

Stern, L. (2004). Effective assessment: probing students understanding of natural selection. *Educational Research, 39*(1), 12-17.

Treagust, D. F. (1986). Evaluating students' misconceptions by means of diagnotic multiple-choice items. *Research in Science Education, 16*, 199-207.

Treagust, D. F. (1988). Development and use of diagnotic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*, 159-170.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1993). Research on alternative conceptions in science. In D. Gabel. (Ed.), *NSTA Handbook: Research in Science Teaching* (pp. 177-209). New York: Macmillan.

White, P. J., Heidemann, M. K., & Smith, J. S. (2013). A new integrative approach to evolution education. *BioScience, 63*(7), 586-594.