Children's Misconceptions and Conceptual Change in Science Education

Justin R. Read[*]
School of Chemistry
The University of Sydney

INTRODUCTION

There is broad consensus among researchers in the education field that individuals should not be thought of as passive recipients of information during instruction, but rather that learners are active constructors of their own knowledge. Prior to beginning school, children have a wealth of experiences, and these have led them to develop a common-sense understanding of their social and natural environment. This is both a desirable fact – as the construction of new knowledge will build on this pre-existing knowledge – and a problem. The problem arises from the fact that the knowledge taught in schools is frequently incompatible with common-sense understandings, and so can impede comprehension. As a result, a reorganisation of existing knowledge is necessary, and it is this process that is usually referred to as conceptual change.

The process whereby conceptual change occurs is of central interest in helping us to understand the process of learning, and is also of considerable importance when considering the design of instruction. Since the incompatibility between some common-sense understandings of the world and accepted scientific explanations is inevitable, it is necessary that instructors be able to affect whatever changes are necessary for comprehension of the scientific explanations to develop.

The purpose of this paper is to discuss some theories of conceptual change, and their implications for instruction, focussed primarily in science education, as the majority of research in conceptual change deals with scientific and / or mathematical concepts. The paper will also discuss some problems in the design of instruction that are not directly considered in the literature.

A NOTE ON TERMINOLOGY

There is much discussion in the literature of the notions of misconceptions, naïve conceptions and alternative conceptions, and many researchers have a preference for one term over another. Sneider

---

[*] Correspondence should be addressed to Justin Read, School of Chemistry, F11, The University of Sydney, NSW 2006 Australia. Email: j.read@chem.usyd.edu.au

This manuscript should be referenced as:
Read, J. R. (2004). Children's Misconceptions and Conceptual Change in Science Education. Available from http://acell.chem.usyd.edu.au/Conceptual-Change.cfm

and Ohadi (1998, p. 66) wrote that “[m]any researchers object to the term ‘misconception’ because, from the student’s viewpoint, the ideas expressed are logical. ‘Preconceptions’, naïve theories’, and ‘alternative frameworks’ have been proposed as better terms for students’ personal views that are at odds with modern scientific theories.” Those researchers who favour a Vygotskian view of situated learning would also object to the term ‘misconception’ on the grounds that a person may possess multiple, alternate mental representations of the same phenomena (Spada, 1994). Whilst the term ‘misconception’ emphasises the wrongness of a student’s conception, and can thus be seen as critical of the holder of the concept, it should be recognised that alternate term like ‘naïve theory’ are also value-laden. It seems to me that the term ‘naïve theory’ can be criticised for its implicit comment that such theories are held by the credulous and unsophisticated. This is inappropriate, especially if the concept is one like the Aristotlean notion that “motion requires a mover” (Gentner *et al.*, 1997), which held sway for thousands of years until overturned by Newton’s Laws of Motion. (Newton’s First Law states that an object in motion will remain in motion unless acted upon by a net external force.) To describe such a concept as naïve seems to me to be disrespectful both of those who held such views in the past, and of the importance of experience as a teacher.

It should also be noted that a researcher’s choice of terminology gives insight into their epistemological views. Sneider and Ohandi’s (1998, p. 66) preference “to retain the original term ‘misconception,’ because it emphasises [their] goal – to help students construct for themselves a logical theory … that is in agreement with modern science” clearly shows that they favour an epistemology of replacing an incorrect model with a correct one. By contrast, Hallidén *et al.*’s (2002) use of ‘alternative conception’ shows their belief in a situated epistemology. For this reason, this paper tries to retain the terminology favoured by each researcher when discussing their work.

Research in the area of conceptual change has developed from at least two fields of investigation – developmental psychology and science education – and each will be discussed in turn.

DEVELOPMENTAL PSYCHOLOGY AND THE ORIGINS OF CONCEPTUAL CHANGE RESEARCH

In the field of developmental psychology, the Piaget’s (1950, 1985) ideas about intellectual development long held sway. These ideas were based on the belief that the mind always tends to move towards a position of mental equilibrium, and that cognitive development is driven by a desire to avoid or resolve cognitive conflicts. According to this theory, conceptual change is occurs as a result of development of a child’s logical capabilities, and involves the “domain-general modification of cognitive structures that affect the knowledge acquisition process” (Schnotz *et al.*, 1999, p. xiii). Piaget suggested that changes in these structures should influence reasoning ability and knowledge acquisition in all domains (Vosniadou, 1999). However, this focus on global restructuring was criticised as it could not explain why different difficulties with knowledge reorganisation arise in certain domains (Schnotz & Preuβ, 1999). Experimental findings that the cognitive capability of children is much higher than Piaget thought (Carey & Gelman, 1991, cited in Schnotz *et al.*, 1999) also led to criticism of his global focus, and, led by Carey (1985, cited in Vosniadou, 1999) the research focus changed to examining domain-specific restructuring.

Carey argued that development involved domain-specific changes in theory. These changes arise from increased knowledge in a domain (resulting from experience or instruction) and result in the restructuring of pre-existing understandings into more coherent theories (for example, the development of naïve physics into theories of mechanics). Thus, Carey suggests that domain-specific development occurs as a result of knowledge acquisition within that domain, rather than Piaget's notion that development is led by changes in logical capabilities (Vosniadou, 1999). Carey's approach is consistent with other research results, such as accounts that specialised cognitive mechanisms exits in the mind to deal with different kinds of information (Hirschfeld & Gelman, 1994, cited in Vosniadou, 1999) and that differences between novices and experts in problem solving within a domain are strongly related to knowledge organisation (Voss, 1989).

A fundamentally different approach to conceptual change can be traced to the theories of Vygotsky (1962, 1978). The Vygotskian view of cognitive development as an enculturation process casts concepts as cognitive tools, and these tools both originate from, and are used in human practice within a social context. Vygotsky believed that the tools acquired from everyday experience where closely related to real phenomena, but lack coherence, whereas those acquired in a school environment were coherent but were isolated from real phenomena by the context in which they were acquired. Thus, the purpose of instruction is to help bring these tools together, so that concepts acquired from everyday experience could be integrated into a coherent framework, and the tools acquired from school instruction become usable in everyday situations. Whether such a degree of integration is feasible in a practical sense is open to debate (Schnotz *et al.*, 1999).

SCIENCE EDUCATION AND THE CONCEPTUAL CHANGE MODEL

In the area of science education, in a move a way from the Piagetian focus, Driver and Easley (1978) advocated a focus "more on the actual content of the pupil's ideas, and less on the supposed underlying logical structures" (p. 76). Much research has been done (and continues to be done) on identifying the pre-existing beliefs and misconceptions that students bring to the science classroom.

Workers such as Viennot (1979, cited in Posner *et al.*, 1982) and Driver and Easley (1978) recognised that many of these misconceptions are robust, and persist despite teaching intended to correct them. This, coupled with their own studies into the learning of special relativity (see Posner *et. al.*, 1979, cited in Posner *et al.*, 1982), led Posner *et al.* to propose a model to describe "the substantive dimensions of the process by which people's central, organising concepts change from one set of concepts to another set, incompatible with the first" (Posner *et al*., 1982, p. 211). This conceptual change model is illustrated in Figure 1.

Under the conceptual change model, there are four conditions which must be met in order for conceptual change to occur. These conditions are (Posner *et al.*, 1982):

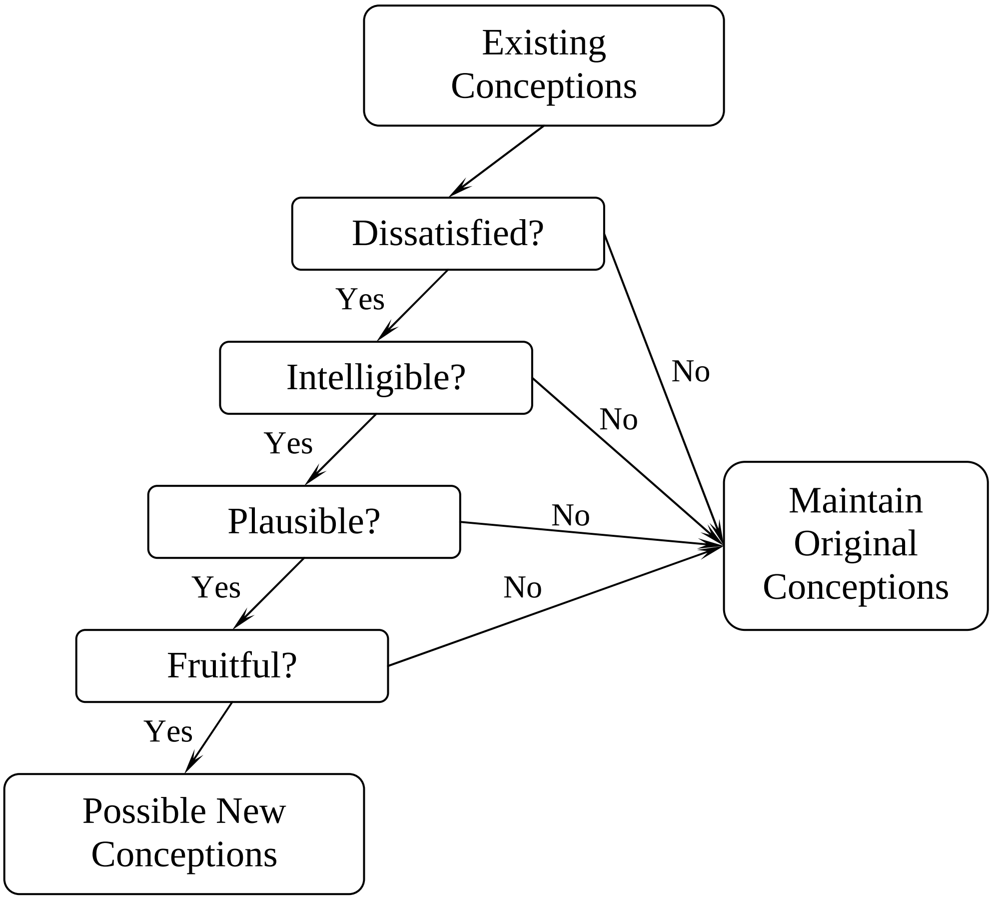

Figure 1: Posner *et al.*'s (1982) Conceptual Change Model – adapted from Dole & Sinatra (1998).

1. *There must be dissatisfaction with existing conceptions.* The process of building a new cognitive structure, or modifying an existing structure, requires active participation and effort on the part of the learner. A person is unlikely to make such an effort without a motivation, and this arises

from dissatisfaction with the present concept, usually due to a lack of faith in the capacity of the existing concept to solve presented problems or resolve anomalies.

2. *A new concept must be intelligible.* This is not to say that it must be fully understood, but rather that the learner "must be able to grasp how experience can be structured by a new concept sufficiently to explore the possibilities inherent in it" (p. 214).

3. *A new concept must appear initially plausible.* To start with, the new concept needs to hold out the promise of being able to resolve the problems that led to dissatisfaction with the current concept. In addition, the new concept will appear plausible if it appears consistent with other existing knowledge. For example, some of the initial resistance to geological evidence that the Earth is billions of years old can be traced to the implausibility of such a result in the light of knowledge existing at that time, as physicists had no theory that could explain how the sun could provide energy for such a period of time.

4. *A new concept should suggest the possibility of a fruitful research program.* That is, it should actually resolve the problems that the original concept could not. In addition, it should have the potential to be extended, opening up new areas for investigation.

It should be noted that Posner *et al.* (1982) distinguish between the assimilation and accommodation when dealing with new phenomena. Assimilation involves the use of existing concepts to deal with the new phenomena. By contrast, accommodation occurs when the new phenomena cannot be assimilated, and replacement or reorganisation of existing concepts occurs. The above conceptual change model is describing the process of accommodation.

This model has direct implications regarding how to construct instruction to achieve conceptual change. Instruction should be designed to present anomalies so as to create cognitive conflict. This will create a disequilibrium (in the Piagetian sense), which leads to dissatisfaction with the existing concept, and ultimately to a willingness to accommodate a new concept. According to Posner *et al.* (1982, p. 226), this requires the teacher to adopt the additional role of an "adversary in the sense of a Socratic tutor. In this role, the teacher confronts the students with the problem arising from their attempt to assimilate new conceptions."

This method of instruction can certainly be used to correct some simple misconceptions. For example, suppose a young child believes that a whale is a fish, rather than a mammal. The child could be shown information about whales needing to come to the surface to breathe air. Since fish have gills and can extract oxygen from water, this information is inconsistent with a whale being a fish, and leads to the child being dissatisfied with the whale-as-fish concept. Assuming that the child is familiar with mammals, the notion of a whale as a mammal is both intelligible and plausible. A whale-as-mammal concept is also fruitful, in that it explains why the whale needs to come to the surface to breathe, and it can explain other aspects of whale behaviour (such as producing milk for their young). In this way, an anomaly arising from the whale-as-fish concept has been used to effect a change in the concept. (Chi *et al.* (1994) would take a different approach. They would argue that misconceptions arise due to concepts being placed in incorrect ontological categories. Thus, conceptual change occurs when concepts are correctly re-categorised, as in this case where the concept 'whale' is moved between the ontological categories of 'fish' and 'mammal', but I think this change can be equally well explained using Posner *et al.*'s (1982) approach.)

The conceptual change model can be used qualitatively to identify reasons for conceptual change to explain why some common misconceptions are persistent and difficult to change. For example, the Bohr model of the atom is commonly taught to science students in junior high schools in Australia and overseas. It leads to the widely held misconception that "[a]toms have electrons circling them like planets around a star" (Horton, 2001) – a misconception that is reinforced by diagrams found in many textbooks, such as the illustration of a sodium atom shown in Figure 2, and the "diagram of the Bohr orbits and the corresponding energies for an electron in the hydrogen atom, [in which] [e]ach arc represents a portion of an orbit" from Cotton *et al.* (1987, p. 36) seen in Figure 3.

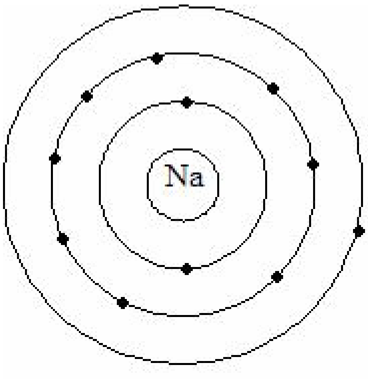

Figure 2: A typical textbook Bohr model representation of the sodium atom

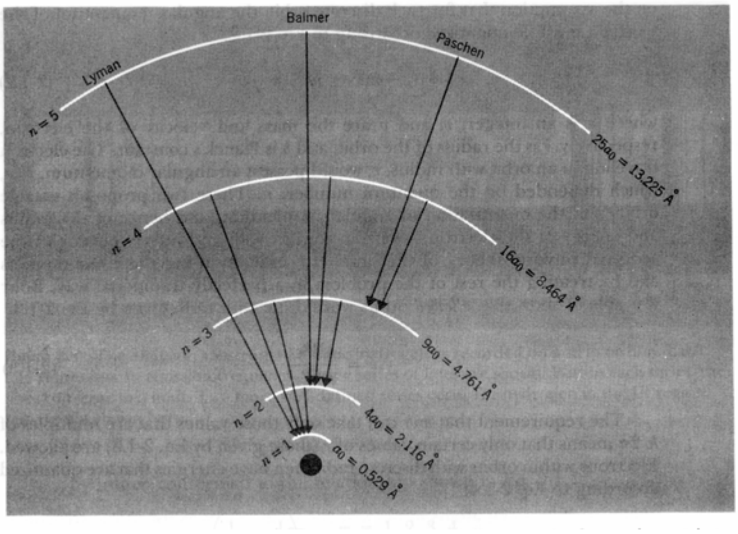

Figure 3: The "Bohr orbits … of hydrogen", from Cotton *et al.* (1987, p. 36).

Research has found that despite teaching of more advanced models, even in introductory University units the Bohr model remains a "very dominant and stable conception" (Müller & Wiesner, 2002, p. 201). I suggest that the reason for its persistence is that more advanced models of the atom, which inevitably involve quantum mechanical notions, lack plausibility. Research has shown that a majority of students hold ontologically and epistemologically realist views on the nature of electrons (Mashhadi & Woolnough, 1998), conceiving of them as tiny solid particles. This view is not easily reconciled with quantum notions of an electron being, simultaneously, a particle and a wave, and leads to these models seeming to lack plausibility.

There is evidence in the literature for improvements in outcomes resulting from instruction designed to restructure incorrect initial conceptions. In a study of conceptual change in astronomy, Diakidoy and Kendeou (2001) compared standard textbook-based instruction with instruction which placed an emphasis on "explanations and demonstrations that would maximise the plausibility and the explanatory power of scientific models in comparison to initial or synthetic conceptions" (p. 13). They found that the students who received targeted instruction showed significant improvement in their understanding compared to the group that received standard textbook-based instruction. Jensen and Finley (1995, cited in Limón, 2001) also reported positive results when using the conceptual change model to teach Darwinian evolution, treating the Lamarckian conception (which historically was replaced by Darwinian evolution) as an initial conception to be challenged and replaced.

The Posner *et al.* (1982) approach has been criticised on a number of grounds, primarily based around the observation that promoting cognitive conflict often fails to produce the radical conceptual change needed for a complicated scientific concept to be understood. Instead, "Students usually patch-up local inconsistencies in a superficial way" (Vosniadou, 1999, p. 4). Other criticisms have been based on the fact that this model fails to consider the social situations within which learning occurs (Limón, 2001), and that it is based on the analogy of children as scientists, which is unhelpful (Caravita & Halldén, 1994), and is of even more questionable value in non-scientific domains (Limón & Carretero, 1999, Limón, 2002).

Chinn & Brewer (1993) identified that science students exhibit seven different responses to anomalous data, and only one of these leads to acceptance of the new data and conceptual change. The other six responses "involve discounting the data in various ways in order to protect the preinstructional theory" (p. 1). These responses are:

- Ignore anomalous data

- Reject anomalous data
- Exclude anomalous data
- Hold anomalous data in abeyance
- Reinterpret anomalous data
- Peripheral theory change
- Theory Change

A number of these responses are, in my view, consistent with the Posner *et al.* (1982) approach. For example, Drake (1980, cited in Chinn & Brewer, 1993) noted that the observations of Galileo were rejected as anomalous data because they did not accord with the Aristotelian view of the nature of the solar system. The anomaly was explained as being an artefact created by the telescope itself, and in this way the pre-existing belief in the correctness of Aristotle's model was protected. This can equally be explained under the conceptual change model as a new concept that lacked plausibility. Similarly, Chinn and Brewer (1962) offer, as an example of holding anomalies in abeyance, the case where physicists in the late 1800's were aware that the known details of the orbit of Mercury were inconsistent with Newtonian mechanics (Kuhn, 1962, cited in Chinn & Brewer, 1993), but this did not lead them to "give up Newtonian theory. They just assumed that there would eventually be a solution within the Newtonian framework." (p. 9) This can equally be considered an example where the anomalous data has not led to sufficient dissatisfaction with the existing theory. Taking an example from chemistry, Arrhenius' theory of acids and bases was confronted with the anomaly that ammonia exhibits all the properties of bases, but cannot be a base under this theory. In response, Arrhenius proposed a new definition of a base that allowed ammonia as an exception – this is an example of peripheral theory change, but can again be considered as an example where there was insufficient dissatisfaction to lead to conceptual change.

These examples do highlight a significant weakness in the conceptual change model – its failure to directly consider the learner as an individual. It assumes that the presentation of data that "clearly – for the experimenter or the teacher – contradicts children's or student's ideas beliefs or theories" (Limón, 2001, p. 360) will produce cognitive conflict, and thus lead to dissatisfaction with the existing conception. This presupposes that the existence of a conflict will automatically lead to dissatisfaction – a supposition that completely ignores the individual. Since conceptual change requires effort on the part of the learner, the issue of motivation needs to be considered. As Dole and Sinatra (1998) pointed out in their cognitive reconstruction of knowledge model, dissatisfaction with an existing concept is only one motivating factor that influences whether a learner will put in the effort needed for conceptual change to occur – they identified other factors including social context and personal relevance. So, for example, if a learner is studying an area merely to pass an exam (an extrinsic motivation) in an area that they see as peripherally relevant to their careers, they may recognise the existence of a conflict but lack the motivation to do anything about it, as it lacks a personal relevance for them – evidence of this can be found in my own research work on Veterinary Science students studying first year Chemistry (Read *et al.*, 2003, 2004).

The conceptual change model is also predicated on the assumption that it is necessary for initial conceptions to be replaced with more correct, scientific theories, and that there is not room for the co-existence of different representations. This has been criticised from the Vygotskian perspective for its failure to recognise that knowledge is always situated in a human context (Caravita & Halldén, 1994). Under this approach, naïve conceptions and prior learning are "neither an obstacle nor a prerequisite for conceptual change. The learner begins without using appropriate tools and must learn to become an effective tool user." (Mayer, 2002, p. 106) This involves learning to distinguish between different contexts, so that appropriate concepts (or tools) are used in appropriate situations (Spada, 1994).

Consider, for example, a conception that an object will only remain in motion if a constant force is applied to it. This conception was central to Aristotle's theory of motion (Gentner *et al.*, 1997), and is commonly held by children. This is not surprising, as it is a reasonable description based a child's observation of their world – if they push a toy across the floor, it moves at a constant speed when they push with a constant force and it slows and stops if they stop pushing. However, this conception is inconsistent with Newtonian mechanics, where an object will remain in motion unless acted upon by a force, and might be considered a barrier to learning in a school context. Under the conceptual change model, this misconception is likely to be persistent as the Newtonian concept lacks plausibility in light of everyday experience. This would not be the case, however, from the situated perspective – the Aristotlean notion is fruitful in everyday situations, and can easily be retained. From this perspective, instruction on the Newtonian concept should consider it as one of multiple mental representations that a student might hold, and then focus on its use as a tool for resolving problems in situations where the Aristotlean representation is inappropriate (Spada, 1994). Many researchers who focus on the replacement of misconceptions recognise that so called naïve conceptions continue to be used in restricted contexts, even after the correct scientific has been accommodated (Wiser & Amin, 2001, for example). In this sense, there has been a move towards the acceptance of multiple representations, in line with the situated perspective.

The conceptual change model has also been criticised by diSessa (1993), as it assumes that students' pre-existing alternative conceptions are internally coherent. By contrast, diSessa argues that these conceptions consist of fragmented pieces of knowledge, termed p-prims (phenomenological primitives), which must be reorganised and made internally coherent to produce explanations. Under this theory, cognitive conflict is ineffective as an instructional approach as it is aimed at challenging a coherent system of belief, and such a system is not present. Instead, diSessa argues that p-prims must be reused and integrated to produce scientific understanding, and that "building a new and deeper systematicity is a superior heuristic to the 'confrontation' approach that many theorists have taken" (diSessa, 1993, p.51, cited in Limón, 2001, p.368). The problem (in my view) with this line of argument is that it requires alternative conceptions to lack coherence, and whilst the question of the coherence of misconceptions remains unresolved, there is evidence in the literature suggesting that misconceptions can have a high level of coherence.

VOSNIADOU'S CONCEPT OF SYNTHETIC MODELS

Vosniadou (1994) studied the mental models students construct about the shape of the Earth in grades 1, 3 and 5 in a number of countries. She found that young children seem to start with a mental model of the Earth that is a flat or rectangular disc, which is supported from below by the ground, and is surrounded by the sky and other objects (such as the sun and moon) above its flat top. These models seem consistent with a child's everyday experience, and so are termed initial models, as they do not show any influence from instruction about a spherical Earth. Older children were often found to have models that combined aspects of both the initial model and the spherical model. These models fell into three broad categories (Vosniadou, 1994, pp. 53 – 54.), illustrated in Figure 4:

- Dual Earth Model – there are two Earths, a flat one on which people live and a spherical one which is a planet up in the sky.
- Hollow Sphere Model – the Earth is a hollow sphere with people living on flat ground deep inside it
- Flattened Sphere Model – the Earth is a sphere that has been flattened at the top and bottom, and these flattened areas are where people live.

Vosniadou termed them 'synthetic models', as they represent an attempt to synthesise apparently contradictory information – everyday experience says that we live on flat ground, but the Earth is somehow still a sphere.

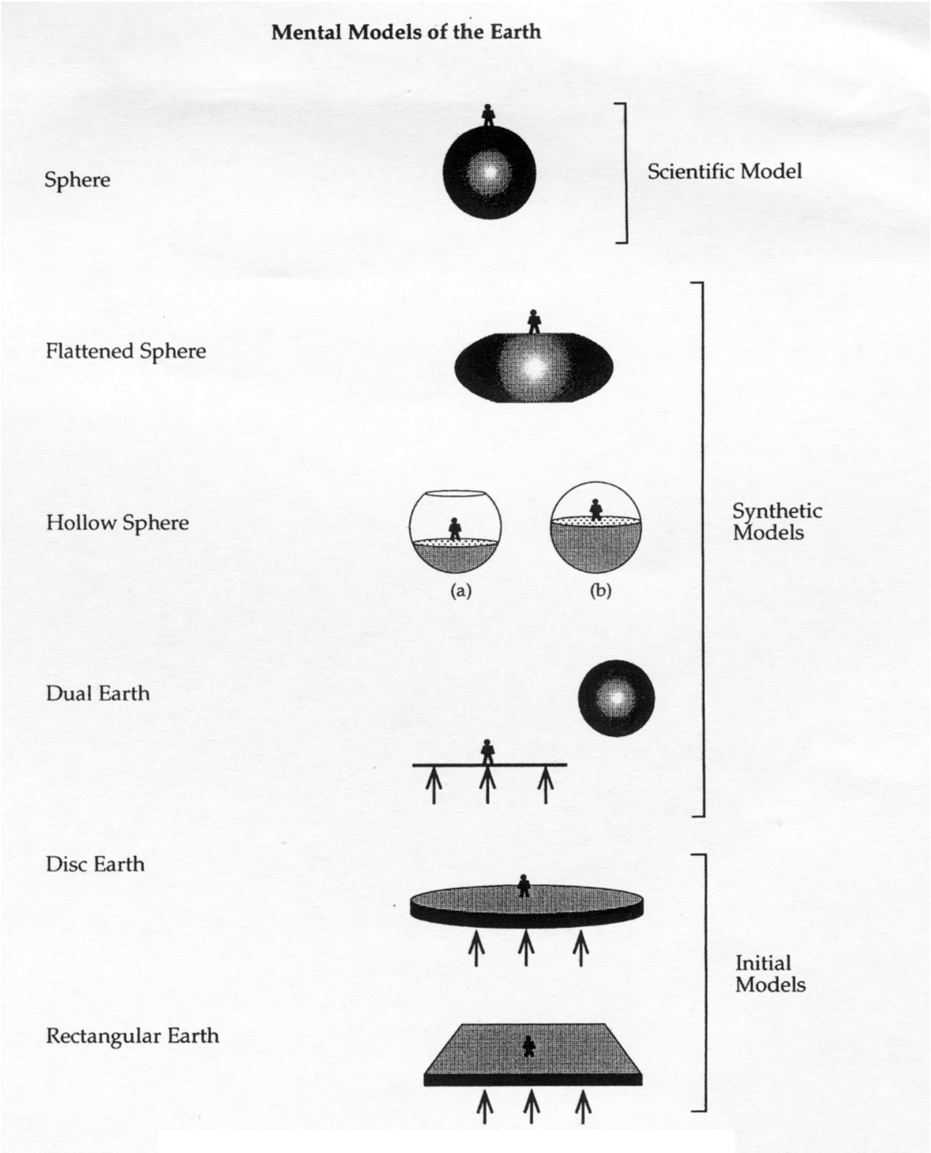

Figure 4: Mental models of the Earth identified by Vosniadou & Brewer (1992, cited in Vosniadou, 1994).

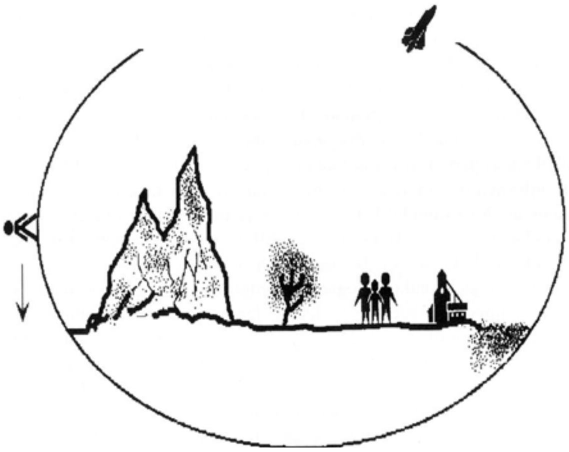

Figure 5: A hollow Earth synthetic model.

An important result from the work of Vosniadou (1994) is that students who use scientific concepts correctly in some cases, but incorrectly in others, do not necessarily have to have a conception that lacks internal consistency – such an alternative conception may be well-defined and internally consistent. Schnotz & Preuβ (1999) offer a detailed account of how a synthetic model may be internally consistent. They describe one such synthetic model (Figure 5) as follows: "The Earth is a sphere; a man walking straight ahead does not reach the end of the Earth because there are mountains and oceans in between; nevertheless, the Earth has an end, which is on the top and can be reached only by a rocket; people cannot fall from the Earth because they are living inside on the flat bottom, but an individual living outside on the spherical surface would, of course, fall down." (p. 201). This notion of internally consistent, but not scientifically accurate, conceptions directly opposes the diSessa (1993) notion that misconceptions arise from fragmentation of knowledge.

Vosniadou (1994) explained these results by describing children as having a pre-existing framework theory which is derived from their observation of the world. This theory possesses both ontological presuppositions (such as unsupported objects fall) and the epistemological presupposition that things are as they appear to be. The development of synthetic models then results from an attempt to accommodate the notion of a spherical Earth with the constraints laid down by this pre-existing framework theory. For example, the hollow sphere model represents an acceptance that the Earth does not have to be supported (ie. it has been reclassified as an astronomical object, rather than a physical object), but retains the up / down notion of gravity, which is a constraint imposed by the framework theory. Under this model, conceptual change is least likely to occur when it requires a revision of the entrenched presuppositions of the framework theory, and this can be used to explain some of the observations that cognitive conflict can be ineffective as an instructional method.

Vosniadou's (1994) approach has clear implications for instruction. She notes (p. 67) that:

> "It is interesting to note that many conceptual conflict producing situations used by science educators confront students' synthetic models rather than the presuppositions of the naïve framework theory responsible for creating these mental models. If students' misconceptions are formed because of inadequate attempts to replace entrenched presuppositions with a different explanatory framework, as our analysis show, the focus of instruction must be the presuppositions and not the misconceptions. For example, telling a child who believes that people live on flat ground inside a hollow sphere, that the Earth is *not* hollow, will not solve the child's problem with the notion of a spherical Earth. Children believe that the Earth is a hollow sphere because they cannot reconcile their perception of a flat Earth with the ideas of roundness and with their presupposition that gravity operates in an up / down fashion. What children need in order to get rid of this misconception is a lesson on gravity and a lesson on how round things can sometimes appear to be flat. Otherwise, one misconception will be followed by another, and the student will remain confused."

IMPLICATIONS FOR INSTRUCTION

Schnotz *et al.* (1999) noted that the "different theoretical views on conceptual change result in different suggestions on how to foster conceptual change" (p. xvi). For example:

- If you consider that naïve knowledge is incoherent, then instruction should aim to promote the development of mental coherence (the diSessa view).
- If you favour the Vosniadou view of synthetic model formation, then instruction should aim to address the incorrect ontological and epistemological assumptions that underlie implicit framework theories.
- If you favour the Chi view that misconceptions arise from incorrect ontological categorisation, then instruction should aim to promote understanding of correct categorisation.
- If you favour a situated view, then conceptual change involves changing the contextualisation of knowledge, rather than reorganising the knowledge itself, and as a result instruction should be aimed at distinguishing between contexts, so that learners can recognise which knowledge structures are useful in which situations.

The issue of instruction designed to elicit conceptual change is widely addressed in the literature. I wish now to consider an issue that is not really discussed in the literature – the issue of misconceptions that are created by methods of instruction.

MISCONCEPTIONS CREATED BY INSTRUCTION

There has been much work done on misconceptions that students possess, on why such misconceptions persist, on how misconceptions might be addressed, and on the origins in everyday experience of many naïve conceptions. However, there is little discussion on the origins of misconceptions found in senior high school and university students.

Take, for example, the Bohr model of the atom. There has been work done on how this model might be taught more effectively (such as Haendler (1982) and Latimer (1983), and more recently Niaz *et al.* (2002)). I have already discussed work that shows the misconceptions associated with this model are persistent, and suggested that the reason for this lies in the initial implausibility of the replacement concepts. I now propose that the origin of this misconception lies in its inclusion in junior science syllabi. Since we know that use of the Bohr model leads to the development of misconceptions, I suggest that its inclusion in the syllabus forces teachers to engage in instruction to develop an understanding of a model that will later actively inhibit learning more advanced theory. This, it seems to me, is counterproductive, especially as the educational objectives satisfied by the

Bohr model could still be met with instruction that moved directly from Rutherord's nuclear model to a simplified version of the quantum model, and without the creation of a persistent misconception.

There is other evidence in the literature for misconceptions created by instruction. In a study of the ability of first year college chemistry students in the United States, Yarroch (1983 and 1985) found that whilst all subjects tested could correctly balance a simple chemical equation (a purely algorithmic problem), over half could not correctly pictorially represent the same equation. That is, whilst the students could convert the unbalanced equation for ammonia synthesis (Equation 1) to the balanced equation shown in Equation 2, over half the subjects could not produce a correct pictorial representation (Figure 6), but rather produced an incorrect representation such as the one shown in Figure 7.

$$N_2 + H_2 \longrightarrow NH_3$$

Equation 1: Unbalanced chemical equation for ammonia synthesis

$$N_2 + 3H_2 \longrightarrow 2NH_3$$

Equation 2: Correctly balanced chemical equation for ammonia synthesis

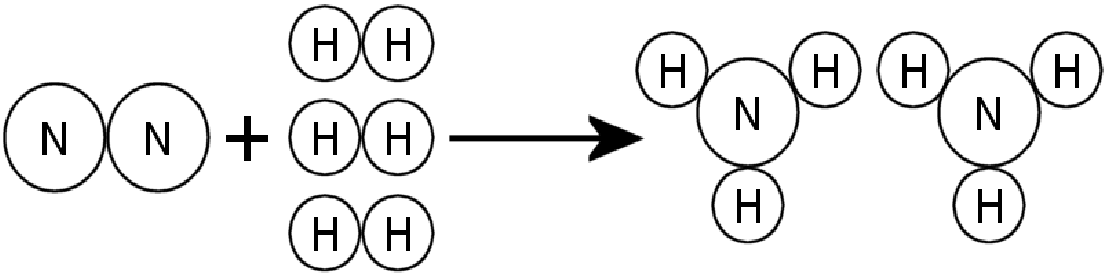

Figure 6: Correct pictorial representation of ammonia synthesis

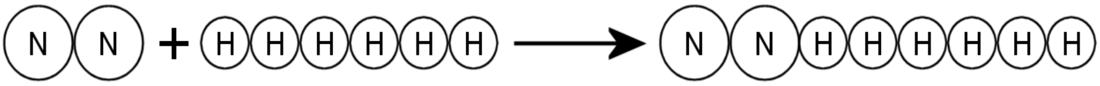

Figure 7: Incorrect pictorial representation of ammonia synthesis

Yarroch's findings are surprising, as they indicate a fundamental lack of understanding of the meaning behind various components of a chemical formula and equation. The additive representation shown in Figure 7 suggests that the American students in the study do not distinguish between coefficients and subscripts in chemical equations, and thus do not have a robust understanding of the nature of molecules. Whilst Yarroch's study does have some limitations (Prabhakar, 2001), its findings are supported (albeit indirectly) by the work of Nurrernburn and Pickering (1987) and Bodner and Domin (1996). However, the study of Prabhakar (2001) found no evidence of this misconception amongst Australian students, and anecdotal evidence suggests that this is not a common misconception in the United Kingdom either (George, 2003).

I suggest that the origin of this misconception, and of the variation between countries lies in the classification of equations used in many American textbooks (such as Silberberg (2000)), and the method of instruction which this classification promotes. In many cases, these textbooks group together equations in classes such as combination (A + B → C) single replacement (A + BC → AB + C) and double replacement (AB + CD → AD + CB). Unfortunately, these classifications are based on superficial similarities, rather than chemical similarities. For example, there are acid-base reactions that are fall into each of these classifications, and there are many distinctly different types of chemical reactions that have a double replacement form (such as precipitation, acid-base, alkene metathesis and condensation). Whilst these classifications are useful in addressing the purely algorithmic problem of balancing an equation, they actively conceal the important chemical distinctions between different reaction types. Although American textbooks are widely used in both Australia and the United Kingdom, this teaching method is not, and the use of these classifications in teaching in the United States may explain some of the fundamental misconceptions discovered by Yarroch. (It should be noted that these textbooks do go on to discuss the more theoretical classification of equation types; however, it would appear that the misconceptions persist, and in this context the teaching of the original classifications is questionable.)

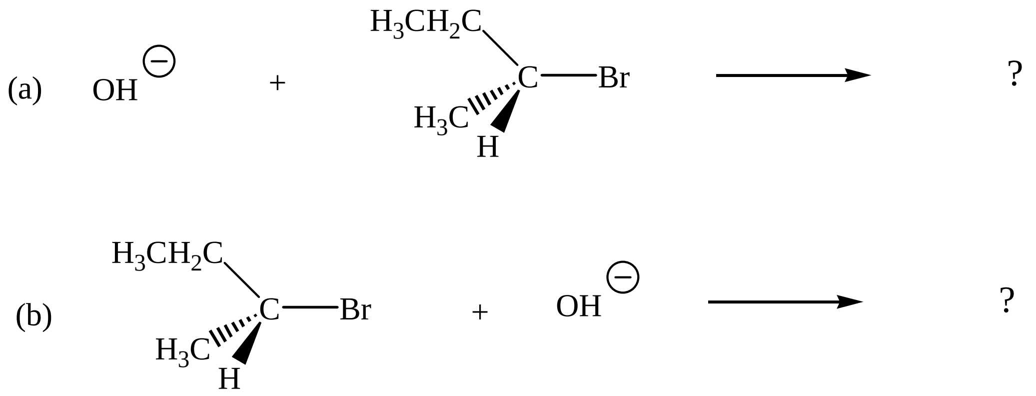

Figure 8: Different representations of the reaction of *(R)*-2-bromobutane with aqueous hydroxide, adapted from Bucat (2004).

Further evidence for misconceptions created by instruction can be found in the work of Bucat (2004) and Ladhams Zieba (2004, cited in Bucat, 2004). In this work, second-year university students were asked to predict the product of the reaction of 2-bromobutane with aqueous hydroxide. This question was presented in two different ways, as illustrated in Figure 8, and in both cases the correct answer is *(S)*-2-butanol, illustrated in Figure 9, resulting from an S_N2 substitution reaction, learnt in first-year university chemistry courses.

(a) (b)

Figure 9: (a) The structure of the correct product, and (b) the incorrect substitution product.

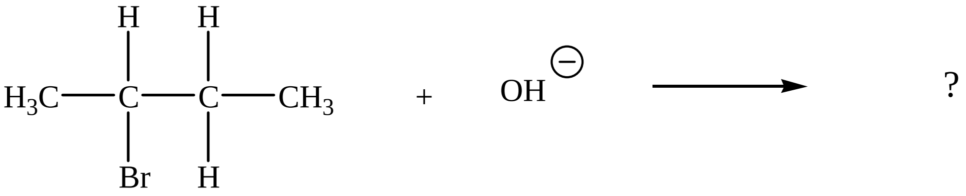

Figure 10: The reaction of 2-bromobutane with aqueous hydroxide, presented in a square planar form.

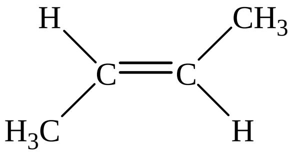

Figure 11: The elimination product predicted by students in the Head *et al.* (2004) study.

These results are strongly suggestive that the students are engaging directly with the representations presented, rather than connecting these representations with the actual substances they represent. For the reactions presented in Figure 8, the correct answer is identified by recognising that the reaction proceeds via attack from the side of the molecule opposite the bromine atom – that is, the orientation shown in Figure 8(a). The reordering of the reactants shown in Figure 8(b) would have no effect on the outcome of the reaction, but the students' answers indicate that they do not understand the mechanism by which the reaction takes place, as they would otherwise recognise that the orientation for the reaction is not that shown in this version of the question.

The results of the Head *et al.* (2004) study provide further evidence for this position – the tetrahedral representations used in Figure 8 are typically those used to illustrate substitution reactions, whereas the square planar representation used in Figure 10 is typically used to illustrate an elimination reaction. The fact that the outcome predicted by the students is heavily dependant on the representation chosen demonstrates that the students are engaging with the representations rather than the substances that they represent. Furthermore, Head *et al.* (2004) found that when the question was asked in words, the representation chosen by the student to represent the question determined the outcome that they predicted – those who drew a tetrahedral representation mostly predicted a substitution product, whilst those who drew a square planar representation mostly predicted an elimination product. I suggest that this indicates a misconception created by instruction as the representations chosen in presenting a question determine the answer provided. The students need not recognise the type of reaction involved, as the representation itself provides this information. The fact that the use of these particular representations for these particular types of reactions occurs in all standard textbooks (such as McMurry (2000) and March (1992)), and is also used in lecturing organic chemistry throughout the world (George, 2004), has the unfortunate side effect of reinforcing this misconception. It is natural for an expert (such as a lecturer) to use the representation that best illustrates the phenomenon under study, but I suggest that instruction involving the deliberate use of less appropriate representations, which are then modified to more appropriate representations, would force students to engage directly with the chemistry involved, rather than simply with the representation of that chemistry. In other words, the representations chosen in presenting a question should not be able to be used to predict its answer

CONCLUSION

Whilst the views of conceptual change presented in the literature are diverse, there are some results with which most researchers would agree. Since learning is an active process in which the learner constructs their own knowledge, the task of conceptual change requires effort on the part of the learner. Furthermore, pre-existing knowledge is a critical factor in this process, and the process is a gradual one. Beyond this point, opinions begin to diverge. The four views of conceptual change that have been discussed can be summarised as follows:

- Vosniadou views conceptual change as involving the revision of epistemological and ontological presuppositions of a pre-existing framework theory so that new mental models may be created. Conceptual change occurs in the mind, and prior knowledge is both an obstacle to be overcome and the vehicle through which change occurs.
- Chi views conceptual change as the recategorisation of concepts into their correct ontological categories. Conceptual change occurs in the mind, and prior knowledge is an obstacle to be overcome as it involves incorrectly categorised concepts.

- diSessa views conceptual change as the organisation of knowledge in pieces into a structured, coherent picture. Conceptual change occurs in the mind, and prior knowledge is both the vehicle through which change occurs via the orgnaisation of existing p-prims.
- Sociocultural views (such as those of Ivarsson *et al.*, cited in Mayer (2002)) view conceptual change as the appropriation of cultural tools and learning how and when to use them. Conceptual change occurs in society, and is socially negotiated within a community of practice and so prior knowledge is neither an obstacle to be overcome nor the vehicle through which change occurs.

In addition, I have presented some evidence that the process of instruction can, unintentionally, lead to the creation of misconceptions, just as it can lead to the correction of misconceptions.

REFERENCES

Bodner, G. & Domin, D. (1996). *The Role of Representations in Problem Solving in Chemistry*. Purdue University.

Bucat, R. B. (2004, February). Chemists' levels of operation: A refined framework. Paper presented at the Annual Meeting of the Chemical Education Division of the Royal Australian Chemical Institute, Hobart, Australia.

Caravita, S., & Halldén, O. (1994). Re-framing the problem of conceptual change. *Learning and Instruction. 4,* 89 – 111.

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction. 4,* 27 – 43.

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

Cotton, F. A., Wilkinson, G. & Gaus, P. L. (1987). *Basic Inorganic Chemistry.* (2nd ed.). New York: Wiley.

Diakidoy, I.-A. N., & Kendeou, P. (2001). Facilitating conceptual change in astronomy: A comparison of the effectiveness of two instructional approaches. *Learning and Instruction. 11*, 1 – 20.

diSessa, A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10,* 105 – 225.

Dole, J. A., & Sinatra, G. M. (1998). Reconceptualizing change in the cognitive construction of knowledge. *Educational Psychologist. 33* (2/3), 109 – 128.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education. 5,* 61 – 84.

Gentner, D., Brem, S., Ferguson, R. W., Markman, A. B., Levidow, B. B., Wolff, P. & Forbus, K. D. (1997). Analogical reasoning and conceptual change: A case study of Johannes Kepler. *The Journal of the Learning Sciences. 6* (7), 3 – 40.

George, A. V. (2003, October, 10). Personal communication.

George, A. V. (2004, April, 30). Personal communication.

Haendler, B. L. (1982). Presenting the Bohr atom. *Journal of Chemical Education. 59* (4), 372 – 376.

Hallidén, O., Petersson, G., Scheja, M., Ehrlén, K., Haglund, L., Österlind, K. & Stenlund, A. (2002). Situating the question of conceptual change. In M. Limón & L. Mason (Eds.). *Reconsidering Conceptual Change: Issues in Theory and Practice* (pp. 137 – 148). Amsterdam: Kluwer.

Head, J., Bucat, R. B., Mocerino, M. & Treagust, D. (2004, February). Model muddle: Do we distinguish sufficiently between models and reality. Paper presented at the Annual Meeting of the Chemical Education Division of the Royal Australian Chemical Institute, Hobart, Australia.

Horton, C. (2001). *Student Preconceptions and Misconceptions in Chemistry.* http://daisley.net/hellevator/misconceptions/misconceptions.pdf

Latimer, C. J. (1983). Teaching Bohr theory. *Physics Education. 18* (2), 86 – 90.

Limón, M., & Carretero, M. (1999). Conflicting data and conceptual change in history experts. In W. Schnotz, S. Vosniadou & M. Carretero (Eds.). *New Perspectives on Conceptual Change* (pp. 137 – 159). Amsterdam: Pergamon.

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal. *Learning and Instruction. 11*, 357 – 380.

Limón, M. (2002). Conceptual change in history. In M. Limón & L. Mason (Eds.). *Reconsidering Conceptual Change: Issues in Theory and Practice* (pp. 259 – 289). Amsterdam: Kluwer.

March, J. (1992). *Advanced Organic Chemistry: Reactions, Mechanisms and Structure.* (4th ed.). New York: Wiley.

Mashhadi, A., & Woolnough, B. (1998). Students' Conceptions of the "Reality Status" of Electrons. Paper presented at the Annual Meeting of the Singapore Educational Research Association, Singapore.

Mayer, R. E. (2002). Understanding conceptual change: A commentary. In M. Limón & L. Mason (Eds.). *Reconsidering Conceptual Change: Issues in Theory and Practice* (pp. 101 – 111). Amsterdam: Kluwer.

McMurry, J. (2000). *Organic Chemistry.* (5th ed.). London: Brooks / Cole

Müller, R., & Wiesner, H. (2002). Teaching quantum mechanics on an introductory level. *American Journal of Physics. 70* (3), 200 – 209.

Niaz, M., Aguilera, D., Maza, A., & Liendo, G. (2002). Arguments, contradictions, resistances and conceptual change in students' understanding of atomic structure. *Science Education. 86*, 505 – 525.

Nurrenburn, S. & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education. 64*, 508 – 510.

Piaget, J. (1950). *The Psychology of Intelligence.* London: Routledge & Kegan Paul.

Piaget, J. (1985). *The Equilibration of Cognitive Structures.* Chicago: University of Chicago Press.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Towards a theory of conceptual change. *Science Education. 66* (2), 211 – 227.

Prabhakar, C. (2001). *Manipulating Chemical Equations: The* Bête Noire *of Junior Chemistry Students.* Sydney: The University of Sydney.

Read, J. R., George, A. V., Masters, A. F., & King, M. M. (2003). Unpublished results.

Read, J. R., George, A. V., Masters, A. F., & King, M. M. (2004, February). Correlation between individual student perception of understanding and examination performance in chemistry 1 for vet science. Poster presented at the Annual Meeting of the Chemical Education Division of the Royal Australian Chemical Institute, Hobart, Australia.

Schnotz, W., Vosniadou, S., & Carretero, M. (1999). Preface. In W. Schnotz, S. Vosniadou & M. Carretero (Eds.). *New Perspectives on Conceptual Change* (pp. xiii – xxiv). Amsterdam: Pergamon.

Schnotz, W., & Preuβ, A. (1999). Task-dependent construction of mental models as a basis for conceptual change. In W. Schnotz, S. Vosniadou & M. Carretero (Eds.). *New Perspectives on Conceptual Change* (pp. 193 – 222). Amsterdam: Pergamon.

Silberberg, M. S. (2000). *Chemistry: The Molecular Nature of Matter and Change.* (2nd ed.). Boston: McGraw Hill.

Sneider, C. I. & Ohadi, M. M. (1998) Unraveling students' misconceptions about the Earth's shape and gravity. *Science Education. 82*, 265 – 284.

Spada, H. (1994). Conceptual change or multiple representations? *Learning and Instruction. 4*, 113 – 116.

Vosniadou, S. (1994). Capturing and modelling the process of conceptual change. *Learning and Instruction. 4*, 45 – 69.

Vosniadou, S. (1999). Conceptual change research: State of the art and future directions. In W. Schnotz, S. Vosniadou & M. Carretero (Eds.). *New Perspectives on Conceptual Change* (pp. 3 – 13). Amsterdam: Pergamon.

Voss, J. F. (1989). Problem solving and the educational process. In A. Lesgold & R. Glaser (Eds.). *Foundations for a Psychology of Education* (pp. 251 – 294). Hillsdale, NJ: Erlbaum.

Vygotsky, L. S. (1962). Development of scientific concepts in childhood. In E. Hanfman & G. Vakar (Eds.). *Thought and Language* (pp. 82 – 118). Cambridge, MA: MIT Press.

Vygotsky, L. S. (1978). *Mind in Society.* Cambridge, MA: Harvard University Press.

Wiser, M. & Amin, T. (2001) “Is heat hot?” Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction. 11*, 331 – 355.

Yarroch, W. (1983). *Teacher Instruction and Student Performance in Balancing Chemical Equations: An Observational Report.* Madison: The University of Wisconsin.

Yarroch, W. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching. 22*, 449 – 459.