SUDHAKAR AGARKAR AND RICHARD BROCK

7. LEARNING THEORIES IN SCIENCE EDUCATION

INTRODUCTION

Learning is a complex, multi-faceted phenomenon and it is therefore unlikely that a single model could explain all aspects of the process. The twentieth century has seen the development of many different models of learning, referred to as learning theories, some of which are discussed below. The theories emphasise different aspects of learning and are based on a range of different assumptions about knowledge. Though one of these theories, constructivism, is seen as the dominant way of thinking about learning in science education, other theories also contain insights for teachers and researchers. In this chapter, various theories will be grouped together under three broad headings, based on a similarity of assumptions: behaviourism, cognitive theory, and constructivism. As the theories outlined below make varied claims about the manner in which humans acquire new information, they lead to different recommendations for teachers' practice. The implications of each of the models in the science classroom are considered at the end of each section. Whilst considering the different theories it is worth holding in mind that each is a model of the learning process and, though no model is a complete description of the world, some are more useful than others. The reader may wish to consider the validity of the assumptions of each model, and the fruitfulness of the teaching approaches suggested.

BEHAVIOURISM

Behaviourism has its foundation in animal studies. Pavlov realised that if a bell was rung when the dogs in his laboratory were fed, the dogs salivary response was stimulated by the sound of the bell, even if no food was set out (Pavlov, 1927). He defined the development of an association between a stimulus (the sound of the bell) and a response (salivation) as conditioning. This stimulus-response link is central to behaviourist models of learning. The theory is concerned only with observable behaviours of learning, and avoids making claims about psychological processes or entities such as mental states or consciousness. These assumptions led to the development of one of the earliest sets of educational principles, Throndike's (1927) 'laws of learning.' For example, Thorndike proposed the law of effect, which suggests that events that occur after a stimulus-response pairing can alter the strength of the connection. The use of praise to reinforce on-task behaviour might be considered a classroom application of this law. Behaviourist principles came to

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dominate teacher education in the 1950's and saw the rise of models of teachers as dispensers of punishment and an emphasis on drill and practice approaches in the classroom. A key behaviourist thinker, Skinner (1958), proposed the idea of teaching machines, devices which would provide the best environment for conditioning. A student would enter their answer to a multiple-choice question into the machine, be given immediate feedback, and be directed to an appropriate follow-up question. These machines might be seen as precursors to contemporary adaptive learning tools that provide learners with personalised educational experiences.

Behaviourism fell out of fashion in science education research due to criticism on a number of fronts. Firstly, its principles were developed from experiments on animals and therefore might not adequately reflect the complexity of human learning (Stewart, 2012). Secondly, some psychologists argue that memory is more than a passive store of conditions and responses (Baddeley, 2000) but behaviourist models do not represent learning as an active process. Finally, certain interpretations of behaviourism have been associated with an authoritarian and teacher-centred model of teaching (Stewart, 2012). Despite these criticisms, some consequences of behaviourist theory still exert an influence on contemporary classrooms.

Implications for Practice

The behaviourist model of learning suggests a number of classroom strategies: the use of repetition as technique for learning skills and memorising factual knowledge; the introduction of classroom routines; the communication of clear learning objectives; the decomposition of complex tasks into a series of increasingly challenging steps; an emphasis on prompt feedback to promote or suppress behaviours; individualised learning programmes to enable students to work at different rates (Stewart, 2012). In the science classroom, behaviourism has been associated with drill-like practice and the transmission of facts and principles. For example, a teacher may focus on testing the verbatim recall of Newton's laws rather than students' ability to apply those principles to novel situations. However, the effectiveness of approaches that focus on rote-learning are contentious. Constructivists have described the highly successful performance on some measures of achievement by Asian science students, who are taught partly through drill-like approaches, as a paradox (Cheng & Wan, 2015). Though the success of Asian science education is a complex phenomenon, and factors beyond the classroom play a role, it might suggest that behaviourist educational strategies should not be lightly dismissed.

COGNITIVE SCIENCE

The second half of the twentieth century saw a reaction against behaviourist models of learning and the development of a novel approach, cognitive science. Cognitive scientists liken the human mind to a computer and therefore assume that learning can be modelled as information processing. This assumption has led to descriptions of learning as the action of a sequence of modules on incoming information. For example, some models of learning propose that a sensory interface initially processes signals from the world, then the preconscious interpreter filters the data before it is relayed to a conscious executive module (Taber, 2013, p. 66). Such models have explanatory power, for example, the action of the preconscious interpreter may explain how tacit conceptions of the physical world develop. Additionally, learning may be described using a model of memory which consists of the central executive (selectively channels information to other modules); the phonological loop (a short-term store of auditory information); the visuospatial sketchpad (a short-term store of visual information); and the episodic buffer (links visual and auditory information) (Baddeley, 2000). This model suggests that students might readily engage in a verbal and visual task at the same time, but completing two visual tasks simultaneously would be challenging.

The assumption that learning can be represented as a series of processes led to the development of models that distinguished different types of learning. For example, Robert Gagné (1965) assumed that different teaching approaches are appropriate for supporting different varieties of learning. Rote learning may be suitable for acquiring verbal information, such as the sequence of types of wave in the electromagnetic spectrum, but more complex approaches are required to help a learner acquire the skill of problem solving. A separate research programme was developed from the work of scientists attempting to create computer programmes that replicated human behaviours. Researchers such as Allen Newell and Herbert Simon began to study the behaviour of experts on simple tasks such as puzzles and games in order to catalogue the strategies they used. This work influenced researchers in science education and a number of approaches have sought to describe the differences between expert and novice learners or to catalogue the strategies students use when encountering new ideas in the classroom. The models of cognitive theory, developed by these and other research programmes, are diverse and too numerous to examine in detail in this chapter. For the interested reader Reif's (2008) book, *Applying Cognitive Science to Education*, presents a comprehensive discussion of ideas. Just as researchers have attempted to describe the strategies learners use, individuals may develop an awareness of their own learning processes. The study of metacogntion, that is thinking and knowledge about one's own cognitive processes (Flavell, 1979), is an established area of research on cognition in science education. A metacognitve model of learning would include systems that consciously regulate learning and, in general, such reflexive awareness is seen as beneficial to learning in the science classroom.

Cognitive models of learning have attracted criticism for their failure to address aspects of learning such as emotions, tacit skill acquisition and holistic phenomena like understanding (Haugeland, 1978). Critics have also highlighted that the narrow focus of cognitive science on the individual mind presents a limited model of learning. Though this criticism may be true of early research, a number of theorists, for example Bandura (1971), expanded the scope of cognitive theory to develop a social cognitive theory that has been widely used in research in science education. In Bandura's model a reciprocal relationship between the individual and the social environment is assumed. Changes in a student's understanding trigger responses from their teachers and peers, and vice versa.

Implications for Practice

A variety of models developed by cognitive scientists has led to a number of suggestions for classroom practice. As discussed, the approach of cognitive science is to represent cognition as a series of information processing systems. Therefore, the recommendations generated tend to be specific and focused on a particular aspect of cognition, rather than general approaches. Some examples are shown below:

- Research suggests that working memory is relatively limited and therefore 'chunking,' that is dividing content into smaller units, may assist with the retention of ideas (Taber, 2014, p. 166).
- Encoding memories in both visual and verbal forms may make them more stable (Reif, 2008, p. 95), so teaching with both visual and verbal transmission of information may be more memorable.
- Supporting students' ability to regulate their own thinking may make them more effective science learners.

CONSTRUCTIVISM

Constructivism is associated with a group of theories about learning that are a subset of cognitive theories, as they present propositions about information processing. However, constructivist thinkers go beyond the assumptions of cognitive science and, though a range of different varieties of constructivism exist, tend to share broadly similar axioms about learning:

- Learning science is an active process.
- Learners come to the science classroom with pre-existing ideas about many natural phenomena, which have an effect on their subsequent learning.
- It is possible to meaningfully model learner's knowledge as conceptual structures which have some commonalities but also display idiosyncratic features.
  Adapted from Taber (2009, p. 123)

Jean Piaget is often described as the founding thinker of constructivism. He proposed a view of learning, labelled genetic epistemology, which described the processes through which learners developed their knowledge of the world. He used earlier thinkers' notion of schemata, frameworks linking together concepts, memories and perceptions, which enable humans to make generalisations about the world, as the basis of his model. Piaget (1952) described two processes by which new information is added to existing schemata: assimilation occurs when novel information is reinterpreted in order to fit with pre-existing knowledge; accommodation involves the modification of an existing schema in order to accept new data. Learning is seen as proceeding through a cycle of assimilation, cognitive disequilibrium, accommodation, cognitive equilibrium and a return to assimilation. For example, a child may develop a schema that links metals with the solid phase at room temperature. Encountering mercury may lead to disequilibrium that causes the child to change their schema, an act of accommodation, before the next assimilation event occurs.

Piaget's ideas influenced David Ausubel (1963) who proposed that meaningful learning involves the integration of novel information into existing conceptual structure, resulting in an idiosyncratic reconstruction of the knowledge by each learner. Meaningful learning is contrasted with rote learning in which newly acquired concepts remain isolated from pre-existing conceptual structure. The repeated action of meaningful learning processes, over an extended period of time, leads to a model of expert knowledge as a highly inter-connected and well-integrated structure. It is assumed that this kind of knowledge organisation allows experts to apply ideas to novel contexts and adopt a flexible approach to problem solving. This model of learning as the development of conceptual structure, led Ausubel to suggest the idea of an advance organiser, information that is communicated to a student to help them integrate subsequent teaching. For example, a teacher may explain the nature of scientific models before teaching atomic bonding. An understanding of models may help a student interpret the nature of claims made about bonding, and to integrate the novel information into their conceptual structure.

Though his research was not influential outside of the Soviet Union till after his death, Lev Vygotsky has become an important constructivist thinker. He developed the construct of the zone of proximal development (ZPD), which he described as the set of tasks which are not accessible to a student working independently, but become achievable with support from teachers or peers (Vygotsky, 1978). This idea prefigured the development of scaffolding (Wood, Bruner, & Ross, 1976), an approach in which a teacher anticipates the difficulties a student may encounter with a task and provides appropriate information to bridge the gap between the required learning and the student's current position. Vygotsky described how a child's spontaneous concepts, or self-generated ideas, might conflict with the academic concepts they are being taught (Vygotsky, 1962). He suggested that spontaneous concepts are 'saturated with experience,' and therefore challenging to integrate with the abstract concepts of formal education (Vygotsky, 1962, p. 108). This idea was to become the foundation of the research programme into children's misconceptions that arose in the late 1970's (see below). A central assumption of Vygotsky's theory was that concepts appear first in the social realm and only subsequently in the psychological domain (Vygotsky, 1931/1981). A student is likely to encounter the scientific concept of force initially in social discussion in a classroom before internalising the notion. A group of constructivist theories, labelled social constructivisms, built on Vygotsky's claim to develop models of learning that emphasise the role of interactions between individuals. Therefore, rather than constructing learning as the result of processing in an individual's cognitive systems, social constructivists describe learning as the adoption of the behaviours and conventions of a particular culture or group. In this conceptualisation, the aim of science education is for students to adopt similar approaches to making sense of the world as experienced scientists. One of the most influential social constructivist learning theories arising out of the work of Vygotsky and others, is activity theory (Engeström, 1987). Activity theory suggests an individual needs to be understood within their relationship to a wider community and encourages sensitivity to the multiple understandings that may be possessed by different members of the community.

The constructivist research programme in science education began in the late 1970s and early 1980s. Keith Taber (2009, p. 113) has labelled five early papers in the field as a 'seminal corpus' for research into children's ideas in science. In the earliest of these papers, Rosalind Driver and Jack Easley (1978) suggested the term alternative frameworks to refer to students' constructions generated to understand the physical world, for example the idea that, during heating, the dimensions of particles themselves expand. These early papers founded a research programme initially directed at cataloguing students' alternative frameworks across a range of topics in science education. Research interest also focused on the manner in which students' initial understandings came to resemble those of experienced scientists, a process known as conceptual change. One of the earliest, and most influential, contributions to this research was the model of conceptual change proposed by Posner and colleagues (1982). The group suggested that a range of cognitive entities, of various types, for example analogies or beliefs about knowledge, is available to an individual at any given time. They labelled this set of resources a conceptual ecology. The assumption that learners have access to a variety of conceptual resources has become an axiom of a number of models of learning in science education (see, for example, diSessa's (1993) knowledge-in-pieces model).

Conceptual change has remained an area of much research activity in science education and many different approaches have been proposed, leading Tyson and colleagues (1997) to categorise the models into three groups: epistemological, ontological and social/affective approaches. Posner and colleagues (1982) argued conceptual change would occur when students became dissatisfied with an existing concept and a plausible and intelligible alternative was available. This kind of model has been classified as an epistemological (i.e. related to the nature of knowledge) approach to conceptual change. The second category of conceptual change contains the ontological model (Tyson et al., 1997) suggested by Chi and Slotta (1993). The central assumption of this approach is that learners categorise novel concepts into one of three major classes: matter, process or mental state. Students may initially misclassify scientific concepts into an inappropriate class, for example they may assume heat has substance-like properties, and conceptual change may occur through the reclassification of heat as a process. The final group of conceptual change theories are those that acknowledge the importance of social or emotional factors

(Tyson et al., 1997). For example, conceptual change may be driven by a desire to avoid the negative emotions associated with conflict between personal models and novel data and the development of coherence may be an emotionally agreeable and hence motivating experience.

Models of learning are necessarily dependent on how researchers conceptualise mental representations of knowledge. This is an area of intense discussion in science education and two major models of conceptual structures exist: knowledge-as-theories and knowledge-as-elements. The knowledge-as-theories position claims that, though they may differ from those of scientists, students' knowledge structures are relatively organised and coherent (Vosniadou, 2007). Conceptual change in this model is seen as a relatively slow process involving the gradual development of students' naïve theories. An alternative position, proposed by diSessa (1993), is that novice learners' thinking is characterised by a range of different elements that are relatively unstructured and inconsistently triggered across contexts. One of these elements, the phenomenological primitive, or p-prim, is seen as an intuitive knowledge structure that supports explanations of the physical world. For example, a proposed p-prim is the sense that, in general, more impetus or less resistance will lead to greater action. This intuition may underlie a number of alternative conceptions, for example, that objects with greater mass take less time to fall to the ground than lighter objects. P-prims are hypothesised to be contextually triggered and, rather than being discarded as the learner develops expertise, the conditions of their activation are adjusted. In this fragmented description of knowledge, learning is seen as the gradual organisation of knowledge elements into structured systems, known as coordination classes, which lead to a consistency in responses across a range of contexts.

The dominance of constructivism in science education may have obscured the arguments of other perspectives on learning (Solomon, 1994) and a number of critics have argued that the constructivist model is flawed (for a detailed summary of the various critiques of constructivism, see chapter 5 in Taber (2009)). Critics suggest that constructivist models of learning require teachers to accept all students' ideas as equally valid (Matthews, 1992) and the theory has been described as culturally imperialist (Bowers, 2007) due to the perception that the constructivist model has been imposed onto cultures which traditionally value knowledge transmission. Matthews (2002), argues that the strategies suggested by constructivism are well-known educational truisms and that the theory's jargon and underlying philosophical assumptions create confusion and inhibit communication. Proponents of constructivism have rebutted these attacks (Taber, 2009) and the assumptions of the programme are still widely accepted within science education.

Implications for Practice

The model of learning presented in constructivism has led to the proposal of a number of different approaches to teaching. The constructivist axiom that the individual student actively constructs knowledge underlies the discovery learning approach. The technique is often associated with Bruner (1961) but similar notions are found in the writing of Piaget and other thinkers. The central assumption of discovery learning is that ‘discovering for oneself’ leads to more effective learning (Bruner, 1961, p. 26). For example, students may be given a list of properties of a range of elements and asked to create a set of groupings based on physical similarities. It is argued that if students actively participate in the development of ideas, in contrast to simply being presented with facts, they will develop more meaningful understandings. Though the technique was popular in the 1960s and 1970s, in recent decades it has been criticised as an ineffective and potentially counterproductive strategy. The criticisms tend to be aimed at ‘pure’ discovery learning, in which a student receives little or no guidance, and Taber (2009, p. 205) argues that ‘carefully guided discovery’ may play a valid role in science education.

The assumption that learning is an active process performed by the individual, suggests a particular conceptualisation of the role of the teacher. Rather than acting solely as a source of knowledge, the teacher is seen as a facilitator of learning, that is they support students’ personal acts of meaning making. Research on children’s understanding of science has led to a general approach to science teaching that encourages teachers to assess students’ pre-existing ideas and then develop, or alter students’ alternative frameworks to facilitate the acceptance of novel material. One much discussed technique for modifying alternative frameworks is the triggering of conceptual (or cognitive) conflict, a recognition of incompatibility between the concepts a learner holds and novel material (Nussbaum & Novick, 1982). In the physics classroom, for example, a student who believes that a resultant force is required for motion at constant velocity might be shown a simulation of an object moving in space, in the absence of external forces. It is suggested that the dissonance between the simulation and the student’s existing idea will cause conceptual change to occur. However, evidence from studies of the implementation of the approach suggest the technique produces mixed results and is challenging to implement in practice.

CONCLUDING THOUGHTS

The complexity and idiosyncrasy of human learning suggests it is unlikely that a single model will ever completely describe its nuances. Each of the theories above may be effective in describing some aspects of learning but other models, which there is insufficient space to examine in this chapter, may contribute to a fuller representation. The interested reader may wish to investigate, amongst others, semiotic, humanistic or neuroscientific theories of learning. It is important to recall, as with any model, the descriptions of learning presented here are incomplete and based on assumptions that are, to a greater or lesser extent, supported by evidence. Debates about the most appropriate manner to model learning may seem abstract and removed from practice. However, assumptions about the nature of knowledge and learning implicitly and explicitly influence the practice of teachers. The adoption of constructivist or behaviourist assumptions will lead to significantly different approaches to classroom practice, variation in teacher-student relationships and alternative interpretations of successful learning. It might seem that an evidence-based evaluation of the strategies suggested by the different learning theories would allow educators to decide which approach would be most effective in their context. However, the theories suggest different learning outcomes are desirable, for example the acquisition of factual knowledge is seen as central in behaviourist models, whereas constructivists emphasise understanding and meaningful learning. It is therefore difficult to develop a measure of effective learning that can be agreed on by the supporters of different models and hence it is challenging to compare the effectiveness of the approaches suggested.

Rather than seeing the multiple models of learning as existing in competition, the existence of a variety of perspectives may be more flexible and powerful than adherence to a single dominant approach. The richest account of learning is likely to involve models at a variety of different levels that account for the role of cultural pressures, social interactions, personal behaviours, cognitive systems, and the action of neurons. Classrooms are not uniform contexts; there is much variation between students in terms of prior knowledge, motivation, areas of interest and in preferred modes of social interaction. A teacher who has access to different approaches to conceptualising learning and a range of different strategies drawn from different traditions is likely to be well placed to cope with the diversity of classroom situations.

Whilst teachers and researchers may make an informed choice to conceptualise learning through a single framework, it is useful to remain sensitive to alternative interpretations. The dominance of the constructivist approach in science education might discourage new teachers and researchers from investigating models and strategies from other theories of learning. If nothing else, it is hoped that this chapter will encourage readers to engage with the different representations of learning that have been constructed and consider what they have to offer to practice or to research.

FURTHER READING

A comprehensive and accessible introduction to different learning theories and their application to teaching practice can be found in:

Schunk, D. H. (2014). *Learning theories: An educational perspective*. Harlow: Pearson Education Ltd.

A good overview of different learning theories in the context of science education can be found in the following chapter:

Duit, R., & Treagust, D. (1998). Learning in science – From behaviourism towards social constructivism and beyond. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 3–26). Dordrecht: Kluwer Academic Publishers.

Frederick Reif has written a broad introduction to the application of ideas from cognitive science to science teaching:

Reif, F. (2008). *Applying cognitive science to education*. Cambridge, MA: The MIT Press.

Keith Taber's book is a good source of discussion on constructivist models of learning in science education:

Taber, K. (2014). *Student thinking and learning in science.* New York, NY: Routledge.

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