International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

Students' conceptions and the learning of science

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Published online: 23 Feb 2007.

INT. J. SCI. EDUC., 1989, VOL. 11, SPECIAL ISSUE, 481–490

Students' conceptions and the learning of science

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This introductory article to the Special Issue of the *International Journal of Science Education* attempts to review the theoretical contexts for research into children's conceptions in science and to identify future directions for research programmes in this field.

Introduction

In the early 1970s research in science education began to focus on the conceptual models that lie behind students' reasoning in particular science domains. Researchers used interviews and other interpretative techniques to investigate and describe the way in which students conceptualize a range of natural phenomena, providing intriguing insights into the child's conceptual world—a world often reflecting a compelling reasonableness, 'but air weighs nothing! How can it have weight—it just floats about' and 'when you throw a ball up your force goes into it. This wears off as the ball goes up, and gravity takes over pulling the ball down.'

At the same time concern was being expressed at the lack of understanding of scientific concepts by school and university students. It was becoming recognized that meaningful learning involved the structured organization of a knowledge system in which concepts take their meaning from the theories in which they are embedded. Methods such as concept mapping and the exploration of semantic networks were developed to probe learners' knowledge structures (West and Fensham 1974, Stewart 1980, Novak and Gowin 1984). These areas of work were also of interest to cognitive psychologists studying learning in formal knowledge domains.

Nearly two decades later there is an extensive literature that indicates that children come to their science classes with prior conceptions that may differ substantially from the ideas to be taught, that these conceptions influence further learning and that they may be resistant to change. (A bibliography of conference proceedings and collections of papers is given at the end of the issue.)

Why is there this growth of interest in students' conceptions in science? Undoubtedly one reason is that the findings addressed the concerns of science educators and teachers directly, illuminating problems of communication and understanding that exist at the heart of the job of teaching. However, a further reason probably lies in the contribution that studies of children's conceptions have made within an emerging 'new perspective' on learning (Osborne and Wittrock 1983, Resnick 1983, Gilbert and Swift 1985, West and Pines 1985, Carey 1986, West 1988). Central to this perspective is the historically important view that learning comes about through the learner's active involvement in knowledge construction. Within this broadly 'constructivist' perspective learners are thought of as building mental representations of the world around them that are used to interpret new

0950–0693/89 $3·00

situations and to guide action in them. These mental representations or conceptual schemes in turn are revised in the light of their 'fit' with experience (von Glasersfeld 1989). Learning is thus seen as an adaptive process, one in which the learners' conceptual schemes are progressively reconstructed so that they are in keeping with a continually wider range of experiences and ideas. It is also seen as an active process of 'sense making' over which the learner has some control.

In as far as it views learners as architects of their own learning through a process of equilibration between knowledge schemes and new experiences, this perspective reflects and builds on the Piagetian research programme. It differs from it, however, in two significant ways. Instead of focusing on the development of general logical capabilities, the new perspective emphasizes the development of domain specific knowledge structures. In addition, whereas the emphasis in the Piagetian research programme has been on the personal construction of knowledge through an individual's interaction with the physical environment, the new perspective also acknowledges to a greater extent the social processes in knowledge construction both at the level of the individual (Edwards and Mercer 1987, Solomon 1987) and within the community of scientists. The writings of Vygotsky have been increasingly influential in shaping thinking about these social and cultural influences as Bruner and Haste (1987) explain:

> (It) is Vygotsky's view that language is a symbol system which reflects sociohistorical development. Thus the set of frameworks for interpretation available to the growing individual reflects the organizing consciousness of the whole culture... (p. 9).

Learning science, therefore, is seen to involve more than the individual making sense of his or her personal experiences but also being initiated into the 'ways of seeing' which have been established and found to be fruitful by the scientific community. Such 'ways of seeing' cannot be 'discovered' by the learner—and if a learner happens upon the consensual viewpoint of the scientific community he or she would be unaware of the status of the idea.

The aim of this special issue is to review the progress made in understanding the development of children's scientific knowledge from this special constructivist perspective and to assess its application to the improvement of students' science learning. Articles in the issue give a picture of the range of current theoretical, empirical and pragmatic concerns. In general the intention is to illustrate issues in the field through accounts of current ongoing enquiries including studies of the nature, status and development of students' conceptions, theoretical perspectives on the process of conceptual change, ways of promoting conceptual change in teaching situations, and metacognition and conceptual change. In this introductory article I outline some of the main trends, research questions and unresolved problems in each of these areas and suggest possible directions for further work.

The nature, status and development of students' conceptions

Studies that have explored students' conceptions in depth have been undertaken in a wide range of domains in science with many hundreds of papers published, although it is notable that there have been fewer studies in biological areas than in the physical sciences. There are now a number of domains that have received considerable attention (including aspects of mechanics, light, electricity, structure of matter and photosynthesis), and from which a useful picture is emerging.

The conceptions originally documented through in-depth investigations in specific domains (for example heat and temperature (Erickson 1979), light (Guesne 1984), mechanics (Viennot 1979) have been identified in a wide range of replication studies suggesting that there may be some commonality in the models that students construct to interpret events in the natural world. This claim has been supported by planned cross-country studies including students' understanding of electricity in five European countries (Shipstone *et al.* 1989) and cross-cultural studies of children's conceptions of the Earth in space (Mali and Howe 1979). While these reveal considerable commonality in the type and prevalence of the conceptions that are reported, there are indications that the different cultural influences on the development of students' conceptions may also need to be taken into account (Hewson and Hamlyn 1983).

A further important development in the field has been the growth of studies that document the progressive evolution of children's conceptions within specific domains during the school years. For example, the study by Nussbaum (1985) of the development of children's ideas about the Earth in space revealed a sequence of conceptions; young children ascribe to a flat Earth notion, this is replaced by a notion incorporating a spherical Earth but with an absolute view of 'up and down', later the directions of up and down are construed in terms of movement away from or towards the Earth. Such cross-age studies have been undertaken in a range of domains including heat and temperature (Strauss and Stavy 1982), material substance (Holding 1987), air (Brook and Driver 1989), living and non-living things (Carey 1985). Baxter reports in this issue the results of a survey of school children's conceptions about a range of simple astronomical phenomena. He identifies features in the progression of the conceptions used by children between ages nine and 16 and indicates how these findings are being used to inform teaching in this domain. Surveys such as this suggest that children may progress in their understandings by passing through a series of intermediate notions which, though they may not be correct from a scientific point of view, may however reflect progress in children's understanding. Such studies inform the longer-term sequencing of teaching topics and provide information about the range and prevalence of prior ideas that may need to be addressed within a teaching sequence.

Marton and his colleagues in Sweden have adopted an approach to the study of conceptions that they call phenomenography. One of the assumptions made within this perspective is that due to various physical and social constraints there are a limited number of ways in which human beings conceptualize phenomena. The study reported by Linder and Erickson in this issue on tertiary students' conceptions of sound was undertaken within this phenomenographic tradition. Studies of conceptions within this perspective use as data not only evidence of the ways students conceptualize phenomena but evidence from the history of ideas in the field; an approach involving a thorough analysis of the history of scientific ideas within specific domains has provided a useful basis for the study of children's ideas by others in the field (Wiser and Carey 1983).

Differences in methodologies have led to different claims being made about the nature and status of children's conceptions. One open question is the extent to which children's conceptions are genuinely 'theory-like', that is having a coherent internal structure and being used consistently in different contexts; this is a view articulated by McCloskey (1983) and Carey (1985). While some studies provide quite strong support for this view (Vosniadou and Brewer 1989) others are more equivocal (Engel Clough and Driver 1986).

Although it would be unwise to overlook various social and cultural influences on children's conceptions and their progressive development during childhood, the emerging picture does hint at children's conceptions in specific domains having much in common. If this is the case, then this has implications for a substantial research programme that could inform curriculum development in science across the school years.

Perspectives on the process of conceptual change

Studies of students' conceptions present us with discrete snapshots in the continual construction and reconstruction of students' knowledge. Although such studies provide valuable insights that can inform curriculum planning and the possible sequencing of ideas for teaching purposes, they do not provide information on the dynamics of change, information that is necessary as a basis for designing approaches to teaching.

The perspective on the way students' conceptions change that has received most attention from science educators, draws a parallel between students' learning and the way in which theory change has been seen to take place in science itself. Students' science learning is seen to involve a process whereby a new theory progressively replaces an earlier theory. The theory change view has been argued by Carey (1985). She distinguishes between conceptual change that involves 'weak restructuring' of learners' conceptions and 'radical restructuring', a process whereby one conceptual structure is replaced by another that differs from it in a number of ways: in the meaning of the individual concepts, the relationship between them and the domains of the phenomena it explains (a distinction also reflected in the terms 'conceptual development' and 'conceptual change' (West and Pines 1985) and 'accretion' and 'restructuring' (Rumelhart and Norman 1981)). Instructional approaches within this view differ in the extent to which students' theory change is seen to take place from 'inside out' through the autonomous actions of the learner, or from 'outside in' through externally provided support. In this issue Nussbaum draws on this parallel between children's learning in science and the way in which science itself proceeds. He identifies distinct perspectives within contemporary philosophies of science and comments on the implications that these perspectives may have for the way in which science lessons are conducted. In particular he considers the issue of rationality, the role of the crucial experiment and the issue of evolutionary or revolutionary change.

As with theory change in science, conceptual change in learners may be the result of many complex factors. Posner *et al.* (1982), drawing in particular on the work of Toulmin on theory change in science, proposed a model that specified that for conceptual change to take place a number of conditions need to be met. Students first need to be dissatisfied with their existing conception, then for this to be replaced a new conception has to be available that can be understood by the learner and which fits with their experience and is useful in the longer term in interpreting and predicting events. In this issue Hewson and Thornley review the studies of classroom conceptual change that have been informed by this model and they indicate how teachers can monitor and appraise the extent to which students in their classes are adopting new conceptions.

Conceptual change in the classroom

Classroom-based studies that are framed by this theory change view of learning have been conducted. In some studies the strategies being adopted to promote conceptual change focus on the dissatisfaction criterion by presenting students with new, possibly surprising, experiences. The approach of challenging students' prior ideas using discrepant events has been well documented (Nussbaum and Novick 1982). However, problems with the discrepant event approach by itself are apparent. Students can avoid seeing or responding to discrepancies. Even when a discrepancy is recognized this by itself does not necessarily enable a student to replace a prior idea with a better alternative.

Other 'experience based' interventions include carefully designed activities that encourage students to differentiate compounded notions, e.g., heat and temperature (Stavy and Berkovitz 1980) or which make more salient those physical attributes that may not be immediately apparent. For example, Séré and Weil-Barais (1989) report positive results in a study designed to promote an understanding of the conservation of matter in which a sequence of carefully designed practical experiences were used to address aspects of students' prior conceptions.

In addition to experience with physical systems, the importance of peer group discussion as a support for conceptual change has been explored and the effectiveness of giving students opportunities through discussion to make their ideas available for reflection and review has been recognized (Champagne *et al.* 1985). In a recent study of the effect of peer discussion on students' conceptual understanding in the context of floating and sinking, Howe *et al.* (1989) report that discussion between children with differing but inadequate views facilitates understanding and that the more advanced children were helped as much as the less advanced.

Some studies focus more on overt instructional approaches designed to help learners construct new models or conceptions. It is recognized that there are topics where students are unlikely to generate the scientific conception for themselves through exposure to critical events or peer discussion and that they require more support in the process of construction of a new theory. One way of doing this is to build on knowledge elements that the learner already has. This approach of using 'bridging analogies' that enable a student to conceptualize a situation in a new way by analogy with a system they understand has been explored with success by Clement and his co-workers (see the article by Clement, Brown and Zietsman in this issue). Their studies in the domain of mechanics indicate that what will work as a 'bridge' cannot necessarily be anticipated and the process of bridging as well as the identification of effective analogies requires empirical study.

Rather than building on students' existing knowledge, an alternative approach is to provide support for students in constructing an alternative theoretical system and then to consider retrospectively which view, their prior conceptions or their newly constructed theory, best fits the evidence (Rowell and Dawson 1984). This approach has been used successfully in computer-based programmes to promote conceptual change in mechanics (White and Horowitz 1988). In such programmes factors such as air resistance and friction can be controlled enabling students to develop stable new conceptions concerning notions which they are then able to apply in more complex, 'real world' environments.

Classroom studies designed to promote conceptual change in a specific domain often use a range of these strategies. Approaches adopted usually provide opportunities for students to make their ideas explicit and then to challenge, extend, develop or replace these using a combination of strategies. The article in this issue by Russell, Harlen and Watts describes the approaches being used in primary school classes with regular class teachers to encourage conceptual development. The study, which was undertaken in the context of teaching and learning about change or state, reports modest conceptual development in the class as a whole, and indicates how, for individual children, the process of change is complex and piecemeal.

Although the process of restructuring of conceptions does appear to occur in an unpredictable way for individuals (Scott 1987), studies undertaken by the Children's Learning in Science Project suggest that some generalizations can be made about the paths that a class of students will tend to take in their thinking during the restructuring process. The project developed a series of teaching schemes for secondary school students in which the students were presented with experiences that they were asked to reflect upon, interpret and test their interpretation through discussion and experimentation. The same schemes of work were used by different teachers who kept a record of the ideas students introduced using diaries and diagnostic tests. A notable feature of the data was the extent to which similar conceptual pathways with their conceptual problems, apparent conflicts and helpful experiences were identified with different classes (Brook 1987, Johnston 1990). This suggests that well-documented studies of conceptual change in classroom settings could usefully inform curriculum development and provide teachers with a helpful map of the 'conceptual ecology' in their classrooms within specific domains.

Alternative perspectives on learning science

Although the theory change view of learning has so far been the most dominant influence on studies of student's classroom learning in science there are other perspectives that deserve attention by science educators.

A perspective that has been described by di Sessa (1988) as a knowledge-in-pieces view portrays intuitive knowledge as a set of context-dependent schemes. Children's science ideas are thus seen as consisting 'of a rather large number of fragments rather than one or even any small number of integrated structures one might call 'theories' (p. 52) and transition to scientific understanding involves the systematic organization of these schemes. The implications for instruction of this perspective are that it is necessary to provide students with a range of experiences within a domain and to support and encourage the systematic and coherent organization of students' interpretations of those experiences.

A further perspective is provided by those who argue for 'situated cognition', a view which holds that human beings have alternative 'ways of seeing' things that are appropriate in different contexts and social situations. (It may be quite appropriate to talk at home about closing the door to keep the cold out.) Learning science from this viewpoint involves students not so much in changing their conceptions but in learning to distinguish the contexts when particular conceptions are appropriate (Solomon 1983).

In the complex business of classroom learning in science, it is likely that all these perspectives, 'theory-change', 'knowledge-in-pieces' and 'situated cognition' have a contribution to make. The question for science educators is not so much which model to adopt but to identify, from the evidence about children's reasoning and an analysis of the structure of the science to be taught, when each may be appropriate. In his article in this issue, which provides a critique of the field, Millar presents a number of arguments concerning the relationship between research on children's learning in science and its implications for teaching. He argues that a constructivist view of learning does not logically entail a particular model of instruction and suggests that a search for a grand theory of conceptual change to inform teaching may be misguided. Instead he argues that a more painstaking approach may be needed in which each domain has its own researched curriculum development programme.

Conceptual change and metalearning

The question as to whether the changes that take place in children's reasoning are accounted for solely in terms of the development of domain specific knowledge has been disputed over the years; an issue that underlies the debate concerning the validity of the Piagetian stage theory. This issue is re-emerging again with a focus on the development of general metacognitive strategies such as reflective awareness about, and deliberate control over, cognitive functioning.

In a recent book Kuhn *et al.* (1988) report a series of investigations into the development of students' scientific thinking skills. The general argument that is supported by their findings is that students' prior knowledge takes the form of naïve theories that undergo successive revision in the face of new experience and information, and that the nature of this revision or coordination process itself undergoes developmental change. They suggest that 'a major development in scientific reasoning skill is the differentiation of theory and evidence and the elevation of the process of theory/evidence interaction to the level of conscious control' (p. 9).

Following in this general line of enquiry, the article by Carey and her co-workers in this issue reports an investigation into children's views of science. They identify through interviews a series of levels in the understandings children have of such features as the nature of hypotheses, the nature of an experiment and the relationships between scientists' ideas and other aspects of their work. The article also reports results from a small scale intervention study designed to develop students' understanding about the nature of scientific knowledge and inquiry.

Programmes such as these, which enhance students' understanding of the nature of the scientific enterprise in the context of developing their domain specific conceptual understanding, highlight the point that the promotion of conceptual change involves metacognitive strategies. The case for this is further developed in the article in this issue by White and Gunstone. They argue that for effective learning to take place, including learning that involves conceptual change—or in their terms 'belief change', then an environment where learners are encouraged to reflect on their understanding and take greater responsibility for their learning, needs to be provided. They report on an action research project in Australian secondary schools that aims to promote metalearning strategies in science and other subjects.

The approaches to teaching implied by the studies described here may require teachers themselves to change their views of their role as teachers and to develop a new repertoire of strategies. The process of change in science teachers' views of their role and the implications these have for teacher education and professional support is an important associated field of work, but one which it has not been possible to address specifically in this issue.

Directions for future work

The documentation of students' scientific conceptions and the way these progress is a field of work that has its roots in the ethnographic tradition with its recognition of the centrality of personal meaning and of individual and cultural differences. Yet despite this orientation, there appear to be strong messages about apparent commonalities in students' conceptions that may have implications for future directions of work in this field.

Studies of conceptual progression

The evidence from a number of carefully conducted studies suggest that children's ideas within specific domains tend to follow certain conceptual trajectories. Moreover, although there is variation at the individual level and there may be specific cultural influences to be considered, the general picture is that there is much in common in the conceptual trajectories for children from different backgrounds and from different countries.

If this is the case, then research effort invested in documenting these could benefit and inform science curriculum planning at an international level. Such studies could also in the longer term, provide the kind of information on which a developmentally-based assessment programme could be built.

Conceptual change

Research has now documented specific prior conceptions that act as 'critical barriers' (Hawkins 1978) to students' further learning in science. An investment of effort into developing and evaluating specific interventions that address such critical barriers barriers could underpin the development of instructional sequences in the future. Soundly researched effective interventions deserve wider attention.

Metacognition and conceptual development

Until recently the alternative conceptions movement has directed its attention to the development of domain specific knowledge. As studies referred to earlier suggest, the involvement and possible development of more generic metacognitive strategies in the conceptual change process is one that the field needs to entertain seriously.

Teacher involvement

However productive the research programmes outlined here might be, their effectiveness in terms of enhancing students' classroom learning will be limited if the implications for teaching and learning are not adopted by teachers. This has implications not only for the dissemination of the products of research through training and professional development programmes but more fundamentally it argues for the involvement of teachers in the research programmes themselves if the divide between research evidence and current pedagogical practice is to be bridged.

Acknowledgements

I am grateful to Brian Holding, Robin Millar and Philip Scott for their comments on an earlier draft of this paper.

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Publishers' Note

Due to pressure on editorial space, we have been obliged to carry one article in the special issue forward to the first issue of volume 12. This is the article by Elsa Feher, entitled 'Interactive museum exhibits as tools for learning: explorations with light'. We offer our apologies to Dr Feher for any inconvenience thus caused.