



Conceptual change: A powerful framework for improving science teaching and learning

Reinders Duit & David F. Treagust

To cite this article: Reinders Duit & David F. Treagust (2003) Conceptual change: A powerful framework for improving science teaching and learning, International Journal of Science Education, 25:6, 671-688, DOI: [10.1080/09500690305016](https://doi.org/10.1080/09500690305016)

To link to this article: <http://dx.doi.org/10.1080/09500690305016>



Published online: 26 Nov 2010.



Submit your article to this journal [↗](#)



Article views: 6808



View related articles [↗](#)



Citing articles: 214 View citing articles [↗](#)

Conceptual change: a powerful framework for improving science teaching and learning

Reinders Duit, IPN – Leibniz Institute for Science Education at the University of Kiel, Germany (email: duit@ipn.uni-kiel.de), David F Treagust, Science and Mathematics Education Centre, Curtin University, Perth, Australia

In this review, we discuss (1) how the notion of conceptual change has developed over the past three decades, (2) giving rise to alternative approaches for analysing conceptual change, (3) leading towards a multi-perspective view of science learning and instruction that (4) can be used to examine scientific literacy and (5) lead to a powerful framework for improving science teaching and learning.

Development of the notion of conceptual change

Historical developments

Research on students' and teachers' conceptions and their roles in teaching and learning science has become one of the most important domains of science education research during the past three decades. Starting in the 1970s with the investigation of students' pre-instructional conceptions on various science content domains such as the electric circuit, force, energy, combustion, and evolution, the analysis of students' understanding across most science domains has been comprehensively documented in the bibliography by Duit (2002a). Two decades ago, research by Gilbert, Osborne and Fensham (1982) showed that children are not passive learners and the way they make sense of their experiences led to this intuitive knowledge being called 'children's science' (p. 623). Findings from many studies over the past three decades show that students do not come into science instruction without any pre-instructional knowledge or beliefs about the phenomena and concepts to be taught. Rather, students already hold deeply rooted conceptions and ideas that are not in harmony with the science views or are even in stark contrast to them. It is noteworthy that there are still a remarkable number of studies on students' learning in science that primarily investigate such students' conceptions at the content level. Since the middle of the 1980s investigations of students' conceptions at meta-levels, namely conceptions of the nature of science and views of learning (i.e., meta-cognitive conceptions) also have been given considerable attention. Research shows that students' conceptions here are also rather limited and naive.

The 1980s saw the growth of studies investigating the development of students' pre-instructional conceptions towards the intended science concepts in conceptual

change approaches. Research on students' conceptions and conceptual change has been embedded in various theoretical frames over the past decades. Initially, Piagetian ideas were applied that drew primarily on stage theory on the one hand and on his clinical interview on the other. Also basic frameworks of the emerging theories of cognitive psychology were adopted. Later, constructivist ideas developed by merging various cognitive approaches with a focus on viewing knowledge as being constructed such as with the Piagetian interplay of assimilation and accommodation, Kuhnian (Kuhn, 1970) ideas of theory change in the history of science and the radical constructivist ideas of people like von Glasersfeld (1989). However, certain limitations of the constructivist ideas of the 1980s and early 1990s led to their merger with social constructivist and social cultural orientations that more recently resulted in recommendations to employ multi-perspective epistemological frameworks in order to adequately address the complex process of learning (Duit & Treagust, 1998).

Recent studies in an edited volume by Sinatra and Pintrich (2003) emphasise the role of the learner's intentions in knowledge change. This volume brings together Bereiter and Scardamalia's (1989) ideas of the intentional learner and those of Pintrich, Marx & Boyle (1993) emphasizing that conceptual change is more than conceptual. It is this emphasis on the impetus for change being within the learner's control that forms the basis of the chapters in the text. The notion of intentional conceptual change is in some ways analogous to that of mindfulness (Salomon & Globerson, 1987, p. 623), a 'construct which reflects a voluntary state of mind, and connects among motivation, cognition and learning'.

Sinatra and Pintrich acknowledge the important contributions to the study of conceptual change from the perspectives of science education and cognitive developmental psychology. However, what becomes increasingly evident in reviewing the literature on conceptual change in this text and others is the general polarisation of researchers in science education and cognitive psychology such that one can read excellent research in one domain that has little reference to research in the other domain. The text by Sinatra and Pintrich brings many of the researchers in these two domains together in one volume but this is not always the case. For example, in the very informative text by Limon and Mason (2002), based on a symposium as part of the activities of the Special Interest Group of the European Association for Research on Learning and Instruction, there are virtually no references to science education and science education researchers who have worked in this area. Our intention is that this review will help overcome this issue of researchers in two domains not referring to each others' work.

The concept of conceptual change

Research on the concept of conceptual change has developed a unique vocabulary because conceptual change can happen at a number of levels and different authors use alternative terms to describe similar learning. The most common analysis is that there are two types of conceptual change, variously called weak knowledge restructuring, assimilation or conceptual capture and strong/radical knowledge restructuring, accommodation or conceptual exchange. Some authors separate knowledge accretion from conceptual change while others include it as a third level. Various author's positions on these contrasting forms of conceptual change have been summarised by Harrison and Treagust (2000).

Consequently, because the term conceptual change has been given various meanings in the literature, the term change often has been misunderstood as being an exchange of pre-instructional conceptions for the science concepts. In this review, we do not use conceptual change in this way. Rather, we use the term conceptual change for learning in such domains where the pre-instructional conceptual structures of the learners have to be fundamentally restructured in order to allow understanding of the intended knowledge, that is, the acquisition of science concepts. In a general sense, conceptual change denotes learning pathways from students' pre-instructional conceptions to the science concepts to be learned (Duit, 1999).

Conceptual change has become the term denoting learning science from constructivist perspectives (Duit, 1999) and has been employed in studies on learning and instruction in a number of domains other than science (Guzetti & Hynd, 1998; Mason, 2001; Schnotz, Vosniadou, & Carretero, 1999; Vosniadou, 1994). An analysis of these studies on conceptual change shows that they primarily take an epistemological, an ontological or a social/affective position, with most studies adopting an epistemological position. As noted in this review, there are clear limitations to taking a single position to understand conceptual change.

An epistemological position

The classical conceptual change approach involved the teacher making students' alternative frameworks explicit prior to designing a teaching approach consisting of ideas that do not fit the students' existing ideas and thereby promoting dissatisfaction. A new framework is then introduced based on formal science that will explain the anomaly. However, it became obvious that students' conceptual progress towards understanding and learning science concepts and principles after instruction quite frequently turned out to be still limited (Duit & Treagust, 1998). There appears to be no study which found that a particular student's conception could be completely extinguished and then replaced by the science view. Indeed, most studies show that the old ideas stay alive in particular contexts. Usually the best that could be achieved was a 'peripheral conceptual change' (Chinn & Brewer, 1993) in that parts of the initial idea merge with parts of the new idea to form some sort of hybrid idea (Gilbert, et al., 1982; Jung 1993).

The best known conceptual change model in science education, based on students' epistemologies, originated with Posner, Strike, Hewson and Gertzog (1982) and was refined by Hewson (1981, 1982, 1996), Hewson and Hewson (1984; 1988; 1992), Strike and Posner (1985, 1992) and applied to classroom instruction by Hennessey (1993). In the conceptual change model, student dissatisfaction with a prior conception was believed to initiate dramatic or revolutionary conceptual change and was embedded in radical constructivist epistemological views with an emphasis on the individual's conceptions and his/her conceptual development. If the learner was dissatisfied with his/her prior conception *and* an available replacement conception was intelligible, plausible and/or fruitful, accommodation of the new conception may follow. An intelligible conception is sensible if it is non-contradictory and its meaning is understood by the student; plausible means that in addition to the student knowing what the conception means, he/she finds the conception believable; and, the conception is fruitful if it helps the learner solve other problems or suggests new research directions. Posner et al. insist

that a plausible conception must first be intelligible and a fruitful conception must be intelligible and plausible. Resultant conceptual changes may be permanent, temporary or too tenuous to detect.

In this learning model, resolution of conceptual competition is explained in terms of the comparative intelligibility, plausibility and fruitfulness of rival conceptions. Posner et al. claimed that a collection of epistemological commitments called the student's 'conceptual ecology' (Toulmin, 1972) mediated conceptual intelligibility, plausibility and fruitfulness. Strike and Posner (1992, pp. 216–217) expanded the conceptual ecology metaphor to include anomalies, analogies and metaphors, exemplars and images, past experiences, epistemological commitments, metaphysical beliefs and knowledge in other fields. The conceptual change model's use of constructs such as conceptual ecology, assimilation and accommodation suggests a constructivist notion built on Piagetian ideas. These conceptual change approaches have proven superior to more traditionally-oriented approaches in a number of studies.

However, a summarising meta-analysis of the large number of studies available is still missing. A decade ago, Guzzetti, Snyder, Glass and Gamas (1993) did provide such a meta-analysis but they only included studies that employed a treatment-control group design. At around the same time, Wandersee, Mintzes and Novak (1994) summarised their extensive analysis of conceptual change approaches with a cautious remark that their analysis gave the impression that conceptual change approaches usually are more successful than traditional approaches in guiding students to the science concepts. However, a problem with research on conceptual change is that it is rather difficult to compare the success of conceptual change approaches and other approaches. Usually different approaches to teaching and learning address different aims and hence it is only possible to evaluate whether the particular aims set have been adequately met. Nevertheless, in summary, if one takes into account attempts to identify key characteristics of efficient teaching and learning approaches based on reviews and meta-analyses of the relevant literature (e.g., Wang, Haertel & Walberg, 1993), it appears that features are relevant that are also at the heart of conceptual change approaches like cognitive activation. We therefore are convinced that conceptual change approaches are more efficient than so called traditional ones. This efficiency depends on the way the approaches are used in classroom practice and whether the potential they have in principle actually leads to the outcome expected.

Limits of the 'classical' conceptual change approaches

Research has revealed that the conceptual change approaches of the 1980s and the early 1990s may be more efficient compared to traditional approaches of teaching and learning science but these approaches are also limited in a number of other respects, the most important of which seem to be as follows.

First, conceptual change primarily has denoted changes of science concepts and principles, that is, cognitive development on the science *content* level. Often it has been overlooked that these changes usually are closely linked to changes of views of the underlying concepts and principles of the nature of science. The research has not taken into consideration that understanding science includes knowledge *of* science concepts and principles and *about* this science content knowledge. In a recent

review of science education research, Fensham (2001) addressed this limitation by stating:

‘Another weakness in the range of alternative conceptions is that the focus in most of the studies is on isolated concepts of science, rather than on the contexts and processes of conceptualisation and nominalisation that led to their invention in science’ (p. 30).

Fensham also pointed to a certain restriction of the kind of content researched so far:

‘Only a tiny fraction have been concerned with concepts that are associated with the environmental, technological, and socio-scientific content, that was beginning to be tried in the 1980s in STS-types of science curricula. Thus, there are few, if any, studies of students’ conceptions of green revolution, endangered species, bio-diversity, ozone hole, greenhouse effect, noise pollution, shelf life, radiation risk, and toxic level’ (p. 29).

Second, there is a certain focus on the rational, that is, on issues following the logic of the science content structure. This rational approach, which holds for science education research and also cognitive science research on conceptual change, has limitations because it does not consider affective measures. This is the area of research that is addressed by the work on intentional conceptual change by Sinatra and Pintrich (2003) and their text contributors. In other words, learning of the science content embedded in learning environments that support the acquisition of these rational issues has been often neglected (Pintrich, Marx & Boyle, 1993). We discuss this issue in more depth later in the review.

Third, the epistemological orientation has been questioned because of the socio-cognitive ways in which individuals learn; for example, the radical constructivist approaches to learning involving an individual’s cognition were overstated (cf. Matthews, 1993). Epistemological views merging radical and social-constructivist approaches appear to be more promising than monistic views proposed by the one or the other side. There have been developments during the past few years towards such inclusive epistemological views that seem to provide not only powerful frames for understanding learning processes as they happen in real learning situations but also may lead to more fruitful teaching and learning environments. There are powerful tendencies now towards theories of teaching and learning science paying equal attention to the individual and social aspects of learning (Duit & Treagust, 1998).

In a similar vein, Vosniadou and Ioannides (1998) provided a critique of classical conceptual change approaches. First, they argue that the conceptual change approaches as developed in the 1980s and early 1990s put too much emphasis on sudden insights facilitated especially by cognitive conflict (see also Limon, 2001). These authors claim that learning science should be viewed as a

‘gradual process during which initial conceptual structures based on children’s interpretations of everyday experience are continuously enriched and restructured’ (p. 1213).

They also point out that conceptual change involves ‘metaconceptual’ awareness of the students. In other words, students will be able to learn science concepts and principles only if they are aware about the shift of their initial metaconceptual views towards the metaconceptual perspectives of science knowledge—again the same notion taken up by Sinatra and Pintrich. Finally, Vosniadou and Ioannides argue in favour of a theory of science learning that includes the individual cognitive development and the situational and cultural factors facilitating it.

Metacognition is seen by Georghiades (2000) as a potential mediator in improvement of conceptual change learning with primary school children, especially in terms of their inability to transfer their conceptions from one domain to another and the short durability of their conceptions. Both the inability to transfer and the short duration of conceptions give rise to problems faced by classroom practitioners. His model of learning draws upon four overlapping areas: conceptual change sets the epistemological background; transfer and durability of scientific conceptions are the problems to be addressed and metacognition is the potential mediator for improving learning.

Alternative approaches to analysing conceptual change

Conceptual change at the content level is closely linked to changes at meta-levels such as views about the nature of science knowledge (McComas, 1998) and meta-cognitive views about learning. However, to date little is known about the *interactions* of these conceptual changes. Research should put more emphasis on that in the coming years.

Student conceptual status

Hewson appears to understand dissatisfaction as a product of the intelligibility-plausibility-fruitfulness interaction between competing conceptions. The conceptual status construct which classifies a conception's status as intelligible, plausible or fruitful (Hewson, 1982; Hewson & Lemberger, 2000; Hewson & Thorley, 1989) is particularly useful for assessing changes to students' conceptions during learning. When a competing conception does not generate dissatisfaction, the new conception may be assimilated alongside the old, which Hewson (1981) called 'conceptual capture'. When dissatisfaction between competing conceptions reveals their incompatibility (Hewson & Hewson, 1984), two things may happen. If the new conception achieves higher status than the prior conception, accommodation, which Hewson calls conceptual exchange, may occur. If the old conception retains higher status, conceptual exchange will not proceed for the time being. It should be remembered that a replaced conception is not forgotten and the learner may wholly or partly reinstate it at a later date. Both Posner et al. and Hewson stress that it is the student, not the teacher, who makes the decisions about conceptual status and conceptual changes. This position harmonises with constructivist learning theory and the highly personal nature of mental models (Norman, 1983).

Studies utilising the notion of conceptual status include that by Treagust, Harrison, Venville and Dagher (1996) which set out to assess the efficacy of using analogies to engender conceptual change in students' science learning about the refraction of light. Following instruction by the same teacher, two classes of students, one of which was taught analogically and one which was not, were interviewed three months after instruction using an interview-about-instances protocol. Factors related to status were identified from the interview transcripts to help in the process of classifying each students' conception of refraction as being intelligible, plausible or fruitful. Descriptors described by Hewson and Hennessey (1992, p. 177) were used as a guide during this process. For example, Hewson and Hennessey explained that for a concept to be intelligible, students must know what

the concept means and should be able to describe it in their own words. For a concept to be plausible, the concept must first be intelligible and students must believe that this is how the world actually is, and that it must fit in with other ideas or concepts that students know about or believe. Finally, for a concept to be fruitful, it must first be intelligible and plausible and should be seen as something useful to solve problems or a better way of explaining things.

Most of the evidence from this study indicated that conceptual change which meets the criteria of dissatisfaction, intelligibility, plausibility and fruitfulness is not necessarily an exchange of conceptions for another but rather an increased use of the kind of conception that makes better sense to the student. This research has shown that while increased status of a conception is possible by means of analogical teaching, it does not necessarily lead to different learning outcomes as measured on traditional tests.

Ontology and conceptual change

Posner et al., Strike and Posner, and Hewson primarily use epistemology to explain conceptual changes and also comment upon in the way that students view reality – which is an ontological position. Others, however, use specific ontological terms to explain changes to the way students conceptualise science entities (Chi et al., 1994; Thagard, 1992; Vosniadou, 1994). In showing that ‘some of the child’s concepts are incommensurable with the adults’, Carey (1985, p. 269) argued for strong knowledge restructuring during childhood and Vosniadou called similar changes radical restructuring and explains that revisions to central ‘framework theories’ (pp. 46–49) involve ontological and epistemological changes. Chi et al. called their strongest ontological changes ‘tree swapping’ and Thagard (1992) also has a strongest change which he calls ‘tree switching.’ Two candidates for these types of change are, heat needs to change from a flowing fluid to kinetic energy in transit and a gene from an inherited object to a biochemical process. There are many other concepts where scientists’ *process* views are incommensurable with students’ *material* conceptions and the desired changes to students’ ontologies are not often achieved in school science. Despite this pessimistic view, this article argues that school students’ material conceptions can be successfully challenged. However, scientific concepts are very complex and what may be suitable for optimising of school science is not always the currently held science view. For example, in modern physics there are two ways of modelling heat – a process way and also a way that draws on change and conservation of ‘thing like entities’.

Consistent with our position is the research of Chiu, Chou and Liu (2002) who adopted Chi’s ontological categories of scientific concepts to investigate how students perceived the concept of chemical equilibrium. These authors argue that ‘although Posner’s theory is widely accepted by science educators and easy to comprehend and apply to learning activities, . . . it does not delineate what the nature of a scientific concept is, which causes difficulty in learning the concept (p. 689).’

Student modelling ability

Models of every kind are used to communicate science outcomes, plan and implement its methods, and models are science’s major learning and teaching tools (Gilbert, 1993; Gilbert & Boulter, 1998). However, many students find the diverse

models that are used to explain science challenging and confusing (Bent, 1984; Carr, 1984; Garnett & Treagust, 1992; Gilbert & Boulter, 1998) although some researchers (Russell, Kozma, Jones, et al. 1997) advocate that learning with diverse models prevents students developing alternative conceptions that are hard to change. This problem is particularly severe for young students and for those students whose abstract reasoning is poorly developed. Grosslight et al. (1991) investigated student/expert modelling abilities in terms of changes to students' *beliefs* about a model's structure and purpose. They classified many lower secondary students as level 1 modellers because these students believe that there is a 1:1 correspondence between models and reality (models are small incomplete copies of actual objects). Some secondary students achieve level 2 where models remain real world entities rather than representations of ideas, and a model's main purpose is communication rather than idea exploration. Experts alone satisfied level 3 criteria that models should be multiple; are thinking tools; and can be manipulated by the modeller to suit his/her epistemological needs. Some students fell into mixed level 1/2 and 2/3 classifications. Because the levels are derived from the way students describe, explain and use models, the levels provide information about the status of students' conceptions and modelling level changes that may provide useful evidence for conceptual changes.

The differences between Grosslight et al.'s three modelling levels also may reflect different ontologies as students need to change the way they think about reality in order to advance from one level to the next. Modelling ability is a particularly useful tool for identifying changing epistemologies and ontologies during science learning. There is a Piagetian flavour to modelling levels because Grosslight et al.'s levels appear to be linear, age and experience dependent. Conceptual status is strongly epistemological and only conceptions that are at least plausible or fruitful are likely to support higher modelling levels. Useful educational similarities seem to exist between conceptual status and modelling levels 1, 2 and 3 (see Harrison & Treagust, 2000) Grosslight et al.'s work suggests that instruction that ignores a student's epistemological status appears futile and monitoring student epistemology is essential if students are to be led along the modelling level 1 to level 3 learning path.

Epistemological and conceptual profiles

A different but useful way to understand students' conceptualising of multiple models is to use Bachelard's (1968) epistemological profile which is based on the notion that people possess more than one way for describing objects and processes and this is especially so in science. For example, mass can be described in everyday terms of 'bigness', measured instrumentally using a spring balance, expressed in dynamic terms like $F = ma$ or relativistically. Scientists use different methods depending on context so why should students not do likewise? What may appear to be a change in conception by a scientist or a student could simply be a different way of describing a conception based on the context in which it is presented and the preference for one conceptualisation or model over another. For instance, many secondary teachers and textbooks simultaneously use the electron shell or Bohr model when discussing atomic structure, use balls or space-filling models to explain kinetic theory and Lewis electron-dot diagrams for bonding; the particular conceptualisation or model often depends upon the context.

Consequently, while the ability to select intelligible, plausible and fruitful representations or conceptions for a specific context is itself a measure of expertise, researchers need to be aware that apparent conceptual changes may in fact be context-driven choices rather than conceptual status changes. In learning settings, Mortimer (1995) proposed the use of conceptual profiles to help differentiate conceptual changes from what are contextual choices.

Affective factors

Several authors, including Posner et al. (1982) and more recently Sinatra and Pintrich (2003), have emphasised to lesser or greater extents the importance of affective factors in conceptual change. The affective factor of motivation involves establishing conducive learning environments and most teachers value social and group learning. It was with these ideas in mind that Pintrich et al. (1993) proposed that a 'hot irrational' explanation for conceptual change is as tenable as cold cognition and argued that students' self-efficacy and control beliefs, classroom social context, 'individual's goals, intentions, purposes, expectations [and] needs' (p. 168) are as important as cognitive strategies in concept learning. Similarly, Dykstra et al. (1992) claim that group factors can advantage concept learning and Vygotsky's theories (van der Veer & Valsiner, 1991) highlight the importance of social and motivational influences. Pintrich et al.'s review of the social and motivational literature highlights the importance of interest, personal and situational beliefs to students' engagement in learning activities. Indeed, they claim that teachers who ignore the social and affective aspects of personal and group learning may limit conceptual change.

Towards multi-perspective views of science learning and instruction

Conceptual change approaches as developed in the 1980s and early 1990s contributed substantially to improving science learning and teaching. However, as outlined previously there are a number of limitations and one-sidedness that have to be overcome during the next few years. There are promising tendencies towards new approaches that are multi-perspective in several ways:

Towards merging the cognitive and affective domains

There is ample of evidence in research on learning and instruction that cognitive and affective issues are closely linked. However, the number of studies on the interaction of cognitive and affective factors in the learning process is limited. There are, for instance, many studies on the relations between interests and acquisition of science concepts. However, these studies are usually restricted to correlations between interests and cognitive results of learning. The interplay of changes of interests and conceptual change is investigated only in a small number of studies. The multi-dimensional framework for interpreting conceptual change by Tyson, Venville, Harrison and Treagust (1997) includes, for instance, an affective domain, but this domain has not been fully elaborated so far. It appears that it is fruitful to merge ideas of conceptual change and theories on the significance of affective factors. It also seems to be most valuable to view the issue of interests in science and

science teaching from the perspective of conceptual change. Clearly, it is an important aim of science instruction to develop interest in much the same way as to develop students' pre-instructional conceptions towards the intended science concepts.

Towards merging moderate and social-constructivist views of learning

Most studies on learning science so far have been oriented towards views of learning that are monistic to a certain extent. Only recently there are powerful developments towards admitting that the complex phenomenon of learning needs pluralistic epistemological frameworks (Greeno, Collins, & Resnick, 1997) in order to adequately address the many facets emphasised by different views of learning. In science education there is a growing number of multi-perspectives views which appear to be rather promising to improve science teaching and learning (Duit, 1998; Duit & Treagust, 1998).

Briefly summarized, multi-perspective frameworks have to be employed in order to adequately address the complexity of the teaching and learning processes. Only such frameworks allow researchers to model teaching and learning processes sufficiently and to address the ambitious levels of scientific literacy briefly presented in the following.

The research papers discussed so far have largely remained committed to one theoretical perspective of conceptual change as a framework for their data analysis and interpretation. In contrast to this approach, Venville and Treagust (1998) utilised four different perspectives of conceptual change to analyse different classroom teaching situations in which analogies were used to teach biology concepts. The perspectives they used are Posner, et al.'s (1982) conceptual change model, Vosniadou's (1994) framework theory and mental model perspective, Chi, et al.'s (1994) ontological category perspective and Pintrich, et al.'s (1993) motivational perspective. They found that each of the perspectives of conceptual change had explanatory value and contributed a different theoretical perspective on interpreting the role that analogies played in each of the classroom situations.

Conceptual change views and scientific literacy

The 1990s saw an intensive debate about scientific literacy inspired by concerns about the educational demands of the 21st century (DeBoer, 2000; Gräber & Bolte, 1997). Later in the 1990s, these discussions were further fuelled by the results of the TIMSS project (Third International Mathematics and Science Studies) that uncovered striking deficiencies in the state of scientific literacy in many countries. More recently, PISA 2000 (Programme for International Student Assessment) (OECD/PISA, 1999) also showed that students' performance in many countries was less than expected. These results provided another impetus for discussion on scientific literacy concepts and on attempts to improve science teaching and learning.

The major features of scientific literacy will be briefly outlined in the following. Driver and Osborne (1998) provided the following four arguments for the need to improve scientific literacy: (1) The economic argument—modern societies need scientifically and technologically literate work-forces to maintain their competencies; (2) The utility argument—individuals need some basic understanding of

science and technology to function effectively as individuals and consumers; (3) The cultural argument—science is a great human achievement and it is a major contributor to our culture; (4) The democratic argument—citizens need to be able to reach an informed view on matters of science-related public policies in order to participate in discussions and decision-making.

The conceptions of scientific literacy in PISA are of particular interest here as cross curricular competencies and science processes are given particular emphases (Fensham & Harlen, 1999; Harlen, 2001). Scientific literacy is seen as the capacity to identify questions and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity. The foci are the following science processes and cross-curricular competencies. Science processes: (1) recognizing scientifically investigable questions; (2) identifying evidence needed in a scientific investigation; (3) drawing or evaluating conclusions; (4) communicating valid conclusions; (5) demonstrating understanding of science concepts. Cross-curricular competencies: (a) self-regulated learning; (b) ability to solve problems; (c) communication and co-operation.

Briefly summarized, the conceptions of scientific literacy include a broad spectrum of different facets and competencies. These ‘visions’ are rather ambitious. The more advanced levels of scientific literacy such as Bybee’s (1997) multi-dimensional level demand a large complexity of teaching and learning processes and conceptual changes as outlined above. It appears that only multi-perspective conceptual change approaches as outlined above are suited to meet these demands.

Improving scientific literacy has become a major concern of science education research and development during the 1990s, in many respects driven by public awareness about the urgent need for a sufficient level of scientific literacy. In a number of countries the disappointing results of students in TIMSS and PISA studies have alarmed a broader public, as well as politicians and school administrators, who demand that school science instruction become more effective. Recently initiated quality development projects (e.g. Beeth, 2001; Prenzel & Duit, 2000; Tytler & Conley, 2001) share the following characteristics (Beeth, Duit, Prenzel, Ostermeier, Tytler & Wickman, 2003): (1) Supporting schools and teachers to rethink the representation of science in the curriculum; (2) Enlarging the repertoire of tasks, experiments, and teaching and learning strategies and resources; (3) Promoting strategies and resources that attempt to increase students’ engagement and interest; (4) Setting constructivist principles into practice. These characteristics imply that a teacher is a reflective practitioner with a non-transmissive view of teaching and learning. Similarly, these characteristics imply that students are active, self-responsible, co-operative and self-reflective learners. Consequently, quality development programs are based on constructivist views of teaching and learning that are at the heart of conceptual change approaches as discussed in the present review.

The impact of research on school practice

Educational research in general appears to be in danger of being viewed as irrelevant by many teachers (Lijnse, 2000). Kennedy (1997), for instance, argued that the ‘awful reputation of educational research’ (Kaestle, 1993) is due to the domination

of basic research by cognitive psychology. Such studies are usually carried out in laboratory settings in order to allow strict control of variables. The price to be paid for a large degree of experimental 'cleanness' is that the results often do not inform the actual practice of teaching and learning. Wright (1993) provided similar arguments to explain that science education research is frequently viewed as irrelevant by policy makers, curriculum developers, and science teachers. He also claims that most science education researchers have little interest in putting into practice what is known.

Mainstream research in the domain of conceptual change, however, is substantially different from the basic research that Kennedy (1997) criticised.

Constructivist research on conceptual change in science education, for instance, has been of an applied research type from the very start in the early 1980s. It is also most fortunate that there was a turn towards applied research in cognitive psychology in the 1990s (Vosniadou, 1996). Hence, most research on conceptual change in principle addresses the needs of educational practice more adequately than traditional forms of educational research. This research also provides powerful means to improve science teaching and learning. However, it has to be taken into account that every research community develops a particular research culture that defines what counts as good research and this may not be in accordance with what teachers expect and need. Hence, there is always a tendency for the research culture to alienate teachers. This also holds for research in the domain of conceptual change (Duit, 2002b).

Research on teachers' views of teaching and learning and their actual teaching behaviour

There is substantial research available on possibilities to set the visions of scientific literacy as outlined above into practice. Anderson and Helms (2001) point to the crucial issue of changing teachers' views of teaching and learning from transmissive towards constructivist orientation. However, research has also shown that a constructivist view, for example, as revealed in interviews, does not necessarily guarantee teaching behaviour that is constructivist oriented (Fischler, 1994). In other words, there may be a substantial gap between teachers' views (their subjective theories) and actions. It is necessary to change teachers' views *and* actions.

More recent video-studies like the TIMSS video study on mathematics instruction in the U.S., Japan and Germany (Stigler, et al., 1999) or the TIMSS-R video studies on science (Roth, et al., 2001) allow the investigation of teachers' actual teaching behaviour in 'normal' practice and compare that to teachers' views about teaching and learning. In order to find out which teaching and learning scripts are dominating in German physics instruction, a video-study comprising a sample of 14 teachers was carried out. Data sources comprise video documents of about 90 lessons on the introduction to electric circuits and the force concept, in-depth interviews with every teacher (including stimulated recall) and various student questionnaires. Only preliminary results are available so far (Prenzel, et al., 2002). However, with regard to the impact of visions of scientific literacy, contemporary constructivist views of teaching and learning, and conceptual change strategies, it turns out that the teachers in this study are not familiar with these issues in the science education literature. Their views of the aims of physics instruction are rather limited. It also appears that most of the teachers interviewed do not hold explicit theories about the teaching and learning

process (Widodo & Duit, 2002; Widodo, Duit & Müller, 2002). Their view of learning seems to be transmissive rather than constructivist. It is particularly remarkable that most of the teachers are not even familiar with the kind of students' pre-instructional conceptions that have to be taken into account when the concepts of the electric circuit and force are introduced. Their views about dealing with pre-instructional conceptions are not informed by conceptual change ideas. Some teachers are aware that students' pre-instructional conceptions have to be taken into consideration but usually they do not explicitly see them as 'goggles' that guide observation and interpretation of everything presented in class by the teacher or the textbook. However, the teaching behaviour of several teachers meets a number of features that are characteristic for constructivist-informed science classrooms (Widodo, Duit & Müller, 2002). They provide, for instance, certain cognitive activation (e.g., by addressing thought provoking problems) or certain features of 'conceptual change supporting conditions' (such as dealing with everyday phenomena). However, the teachers do not employ conceptual change teaching and learning strategies presented in the literature such as Driver's (1989) constructivist strategy, the learning cycle (Lawson, Abraham & Renner, 1989) or the more recent CONTACT-2 strategy by Biemans, Deel and Simons (2001). The dominating way of thinking about teaching physics may be called subject specific. The teachers have a quite substantial and well-organized repertoire of the kind of experiments available and of how to introduce a certain concept. But this subject specific thinking is only rather loosely based on more general views of good science teaching. Briefly summarized, the impact of more recent research ideas and research findings on teachers' views and classroom actions appears to be rather limited in this study. Of course, the small sample investigated may not be representative for German physics teachers as a whole. However, the major findings on teachers' scripts are in accordance with results of other studies on German physics instruction (Baumert & Köller, 2001). Further analysis will be carried out to confirm the preliminary findings.

Bridging the gap between research findings on conceptual change and instructional practice

The rather ambitious competencies affiliated with recent conceptions of scientific literacy demand the kind of multi-perspective conceptual change approaches outlined above. If a substantial part of the students shall achieve at least a minimum of scientific literacy that is needed to address the challenges of the future these approaches should be taken into account. Research has shown that conceptual change informed teaching usually is superior to more traditional means of teaching. Hence, conceptual change may still be a powerful frame for improving science teaching and learning.

The state of theory building on conceptual change has become more and more sophisticated and the teaching and learning strategies developed have become more and more complex the past 25 years. These developments are, of course, necessary in order to address the complex phenomena of teaching and learning (science) more and more adequately. However, the gap between what is necessary from the researcher perspective and what may be set into practice by 'normal' teachers has increased more and more also. In other words, there is the paradox that in order to adequately address teaching and learning processes research alienates the teachers and hence widens the 'theory-practice' gap. The views of teaching and learning

developed in our research field are far from normal classroom teachers' ways of thinking about instruction. The instructional strategies developed by us are far from the routines of normal classes. As research has clearly shown, it is rather difficult to change (in the sense of a conceptual change) teachers' views and teachers' classroom practice. It may be argued that many conceptual change strategies have been developed and evaluated in actual classrooms and often in close co-operation with teachers (e.g., Biemans et al., 2001; Vosniadou, Ioannides, Dimitrakopoulou & Papademitriou, 2001). However, what works in special arrangements does not necessarily work in everyday practice.

The major message of the present paper is that it is necessary to close the gap between theory and practice at least to a certain extent. What research on conceptual change has to offer classroom practice cannot be set into normal practice to a substantial extent. Of course, teacher development programs are essential in order to change teachers' views of teaching and learning and their practice. However, it appears to be also necessary to make these theories more simple and describe conceptual change strategies in such a way that they may become part of teachers' normal routines.

References

- ANDERSON, R. D., and HELMS, J. V. (2001) The ideal of standards and the reality of schools: needed research. *Journal of Research in Science Teaching*, 38, 3–16.
- BACHELARD, G. (1968) *The Philosophy of No. A philosophy of the new scientific mind*. New York: The Orion Press.
- BAUMERT, J., and KÖLLER, O. (2001) Unterrichtsgestaltung, verständnisvolles Lernen und multiple Zielerreichung im Mathematik- und Physikunterricht der gymnasialen Oberstufe [Instructional patterns, insightful learning and achieved literacy in upper secondary mathematics and physics instruction]. In J. Baumert, W. Bos & R. Lehmann, Eds., *TIMSS/III. Dritte Internationale Mathematik- und Naturwissenschaftsstudie. Mathematische und naturwissenschaftliche Bildung am Ende der Schullaufbahn. Band 2: Mathematische und physikalische Kompetenzen am Ende der gymnasialen Oberstufe* (pp. 271–316) Opladen, Germany: Leske + Budrich.
- BEETH, M. (2001) Systemic reform in mathematics and science education in Ohio (USA): 1991–2000. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Bisdikian, G. Fassouloupoulos, E. Hatzikraniotis and M. Kallery, Eds, *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society, Vol. 1* (pp. 198–200). Thessaloniki, Greece: Aristotle University of Thessaloniki.
- BEETH, M., DUIT, R., PRENZEL, M., OSTERMEIER, C., TYTLER, R., and WICKMAN, P. O. (2003) Quality development projects in science education. In D. Psillos, P. Kariotoglou, V. Tselfes, G. Fassouloupoulos, E. Hatzikraniotis & M. Kallery, Eds., *Science Education research in the knowledge based society*. Dordrecht, The Netherlands: Kluwer Academic Publishers (in press).
- BENT, H. (1984) Uses (and abuses) of models in teaching chemistry. *Journal of Chemical Education*, 61, 774–777.
- BEREITER, C., and SCARDAMALIA, M. (1989) Intentional learning as a goal of instruction. In L. B. Resnick et al., Eds, *Knowing, learning and instruction: essays in honor of Robert Glaser* (pp. 361–392). Hillsdale, NJ: Lawrence Erlbaum Associates.
- BIEMANS, H. J. A., DEEL, O. R., and SIMONS, R. J. (2001) Differences between successful and less successful students while working with the CONTACT-2 strategy. *Learning and Instruction*, 11, 265–282.
- BYBEE, R. W. (1997) Towards an understanding of scientific literacy. In W. Gräber & K. Bolte (Eds.), *Scientific literacy* (pp. 37–68). Kiel, Germany: IPN – Leibniz Institute for Science Education at the University of Kiel.
- CAREY, S. (1985) *Conceptual change in childhood*. Cambridge, MA: A Bradford Book. The MIT Press.

- CARR, M. (1984) Model confusion in chemistry. *Research in Science Education*, 14, 97–103.
- CHI, M. T. H., SLOTTA, J. D., and DE LEEUW, N. (1994) From things to process: A theory of conceptual change for learning science concepts. *Learning and Instruction*, 4, 27–43.
- CHIU, M-H, CHOU, C-C, and LIU, C-J (2002) Dynamic processes of conceptual change: Analysis of constructing mental models of chemical equilibrium. *Journal of Research in Science Teaching*, 39, 713–737.
- CHINN, C. A., and 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, 1–49.
- DEBOER, G. E. (2000) Scientific literacy: another look at its historical and contemporary meaning and its relationship to science education reform. *Journal of Research in Science Teaching*, 37, 582–601.
- DRIVER, R. and OSBORNE, J. (1998, April) Reappraising science education for scientific literacy. Paper presented at the annual meeting of the National Association for Research in Science Teaching (NARST), San Diego.
- DRIVER, R. (1989) Changing conceptions. In P. Adey, Ed., *Adolescent development and school practice* (pp. 79–103). London: Falmer Press.
- DUIT, R., and 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, The Netherlands: Kluwer Academic Publishers.
- DUIT, R. (1998, April) Towards multi-perspective views of science learning and instruction. Paper presented at the annual meeting of the American Educational Research Association in San Diego.
- DUIT, R. (1999) Conceptual change approaches in science education. In W. Schnotz, S. Vosniadou, & M. Carretero (Eds.), *New perspectives on conceptual change* (pp. 263–282). Amsterdam, NL: Pergamon.
- DUIT, R. (2002a) *Bibliography STCSE: Students' and teachers' conceptions and science education*. Kiel, Germany: IPN – Leibniz Institute for Science Education ([ushttp://www.ipn.uni-kiel.de/us](http://www.ipn.uni-kiel.de/us))
- DUIT, R. (2002b) Visions, research, and school practice. In R. Cross, Ed., *A vision for science education: Responding to the work of Peter Fensham* (pp. 155–169). London: Routledge Falmer.
- DYKSTRA, D. I. (1992) Studying conceptual change: Constructing new understandings. In R. Duit, F. Goldberg, & H. Niedderer. (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 40–58). Proceedings of an international workshop. Kiel, Germany: IPN – Leibniz Institute for Science Education.
- FENSHAM, P., and HARLEN, W. (1999) School science and public understanding of science. *International Journal of Science Education*, 21, 755–763.
- FENSHAM, P. (2001) Science content as problematic – Issues for research. In H. Behrendt, H. Dahncke, R. Duit, W. Gräber, M. Komorek, A. Kross & P. Reiska, Eds., *Research in science education – Past, present, and future* (pp. 27–41). Dordrecht, The Netherlands: Kluwer Academic Publishers.
- FISCHLER, H. (1994) Concerning the difference between intention and action: Teachers' conceptions and actions in physics teaching. In I. Carlgren, G. Handal & S. Vaage, S., Eds., *Teachers' minds and actions: Research on teachers' thinking and practice* (pp. 165–180). London: The Falmer Press.
- GARNETT, P. J. and TREAGUST, D. F. (1992) Conceptual difficulties experienced by senior high school students of electrochemistry: electric circuits and oxidation reduction equations. *Journal of Research in Science Teaching*, 29, 121–142.
- GEORGHIADES, P. (2000) Beyond conceptual change learning in science education: focusing on transfer, durability and metacognition. *Educational Research*, 42(2), 119–139.
- GILBERT, J. K. and BOULTER, C. J. (1998) Learning science through models and modeling. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 53–66). Dordrecht, The Netherlands: Kluwer Academic Publishers.
- GILBERT, J. K. (Ed.) (1993) *Models and modeling in science education*. Hatfield, Herts, UK: Association for Science Education.
- GILBERT, J. K., OSBORNE, R. J., and FENSHAM, P. (1982) Children's science and its implications for teaching. *Science Education*, 66, 625–633.
- GRÄBER, W., and BOLTE, K. (Eds.) (1997) *Scientific literacy*. Kiel, Germany: IPN Leibniz-Institute for Science Education.

- GREENO, J. G., COLLINS, A. M., and RESNICK, L. B. (1997) Cognition and learning. In D. C. Berliner & R. C. Calfee, Eds., *Handbook of educational psychology* (pp. 15–46). New York: Simon & Schuster Macmillan.
- GROSSLIGHT, L., UNGER, C., JAY, E. and SMITH, C. (1991) Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, 28, 799–822.
- GUZZETTI, B., and HYND, C., Eds. (1998) *Perspectives on conceptual change*. Mahwah, NJ: Lawrence Erlbaum.
- GUZZETTI, B. J., SNYDER, T. E., GLASS, G. V. and GAMAS, W. S. (1993) Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly*, 28, 116–159.
- HARLEN, W. (2001) The assessment of scientific literacy in the OECD/PISA project. In H. Behrendt, H. Dahncke, R. Duit, W. Gräber, M. Komorek & A. Kross, Eds., *Research in Science Education – past, present and future* (pp. 49–60). Dordrecht: The Netherlands: Kluwer Academic Publishers.
- HARRISON, A. G., and TREAGUST, D. F. (2000) Learning about atoms, molecules and chemical bonds: A case-study of multiple model use in grade-11 chemistry. *Science Education*, 84, 352–381.
- HENNESSEY, M. G. (1993, April) *Students' ideas about their conceptualisation: Their elicitation through instruction*. Paper presented at the Annual Meeting of the American Educational Research Association. Atlanta, GA.
- HEWSON, P. W. (1981) A conceptual change approach to learning science. *European Journal of Science Education*, 3, 383–396.
- HEWSON, P. W. (1982) A case study of conceptual change in special relativity: The influence of prior knowledge in learning. *European Journal of Science Education*, 4, 61–78.
- HEWSON, P. W. (1996) Teaching for conceptual change. In D. F. Treagust, R. Duit & B. J. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 131–140). New York: Teachers College Press
- HEWSON, P. W., and HEWSON, M. G. A'B. (1984) The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science*, 13, 1–13.
- HEWSON, P. W., and HEWSON, M. G. A'B. (1988) An appropriate conception of teaching science: A view from studies of learning. *Science Education*, 72(5) 597–614.
- HEWSON, P. W., and HEWSON, M. G. A'B. (1992) The status of students' conceptions. In R. Duit, F. Goldberg, & H. Niedderer. (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 59–73). Proceedings of an international workshop. Kiel, Germany: IPN – Leibniz Institute for Science Education.
- HEWSON, P. W., and LEMBERGER, (2000) Status as the hallmark of conceptual change. In Millar, R., Leach, J., & Osborne, J (Eds.), *Improving science education* (pp. 110–125). Buckingham, UK: Open University Press.
- HEWSON, P. W., and THORLEY, N. R. (1989) The conditions of conceptual change in the classroom. *International Journal of Science Education*, 11, Special Issue, 541–553.
- HEWSON, P., and HENNESSEY, M. G. (1992) Making status explicit: A case study of conceptual change. In R. Duit, F. Goldberg, & H. Niedderer. (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 176–187) Proceedings of an international workshop. Kiel, Germany: IPN – Leibniz Institute for Science Education.
- JUNG, W. (1993) Hilft die Entwicklungspsychologie dem Physikdidaktiker [Does developmental psychology help the physics educator?]. In R. Duit & W. Gräber (Eds.), *Kognitive Entwicklung und naturwissenschaftlicher Unterricht* (pp. 86–107). Kiel, Germany: IPN – Leibniz Institute for Science Education.
- KAESTLE, C. F. (1993) The awful reputation of educational research. *Educational Researcher*, 22(1), 23–31.
- KENNEDY, M. M. (1997) The connection between research and practice. *Educational Researcher*, 26(7), 4–12.
- KUHN, T. S. (1970) *Structure of scientific revolutions*. 2nd edition. Chicago: University of Chicago Press.
- LAWSON, A. E., ABRAHAM, M. R., and RENNER, J. W. (1989) *A theory of instruction: Using the learning cycle to teach science concepts and thinking skills*. NARST Monograph Number One. University of Cincinnati: National Association for Research in Science Teaching.

- LIJNSE, P. (2000) Didactics of science: The forgotten dimension in science education research. In Millar, R., Leach, J., & Osborne, J. (Eds.), *Improving science education* (pp. 308–326). Buckingham, UK: Open University Press.
- LIMON, M. and MASON, L. (Eds.) (2002) *Reconsidering conceptual change: Issues in theory and practice*. Dordrecht, The Netherlands : Kluwer Academic Publishers.
- LIMON, M. (2001) On the cognitive conflict as an instructional strategy for conceptual change: a critical appraisal. *Learning and Instruction*, 11, 357–380.
- MASON, L., Ed. (2001) Instructional practices for conceptual change in science domains. *Learning and Instruction*, 11, 259–429 (Special Issue).
- MATTHEWS, M. (1993) Constructivism and science education: Some epistemological problems. *Journal of Science Education and Technology*, 2, 359–369.
- MC COMAS, W. F., Ed. (1998) *The nature of science in science education – rationales and strategies*. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- MORTIMER, E. F. (1995) Conceptual change or conceptual profile change? *Science & Education*, 4, 267–285.
- NORMAN, D. A. (1983) Some observations on mental models. In D. Gentner and A. L. Stevens (Eds.), *Mental models* (pp. 7–14). Hillsdale, NJ: Lawrence Erlbaum Associates, Publishers Inc.
- OECD-PISA (1999) Measuring student knowledge and skills: A new framework for assessment. Paris: OECD.
- PINTRICH, P. R., MARX, R. W. and BOYLE, R. A. (1993) Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research*, 63, 167–199.
- POSNER, G. J., STRIKE, K. A., HEWSON, P. W., and GERTZOG, W. A. (1982) Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211–227.
- PRENZEL, M., and DUIT, R. (2000, April) Increasing the efficiency of science and mathematics instruction: report of a national quality development programme. Paper presented at the annual meeting of the National Association for Research in science Teaching (NARST), New Orleans.
- PRENZEL, M., DUIT, R., EULER, M., GEISER, H., HOFFMANN, L., LEHRKE, M., MÜLLER, C., RIMMELE, R., SEIDEL, T., and WIDODO, A. (2002) Eine Videostudie über Lehr-Lern-Prozesse im Physikunterricht [A video-study on teaching and learning processes in physics instruction]. *Zeitschrift für Pädagogik*, 48 [45. Beiheft], 139–156.
- ROTH, K. J., DRUKER, S., KAWANAKA, T., OKAMOTO, Y., TRUBACOVA, D., WARVI, D., RASMUSSEN, D., and GALLIMORE, R. (2001, March) Uses of video-based technology and conceptual tools in research: the case of the TIMSS-R Video Study. Paper presented at the annual meeting of the National Association for Research on Science Teaching (NARST), St. Louis, MO.
- RUSSELL, J. W., KOZMA, R. B., JONES, T., WYKOFF, J., MARX, N. and DAVIS, J. (1997) Use of simultaneous-synchronised macroscopic, microscopic and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education*, 74(3), 330–334.
- SALOMON, G., and GLOBERSON, T. (1987) Skill may not be enough: the role of mindfulness in learning and transfer. *International Journal of Educational Research*, 11, 623–637.
- SCHNOTZ, W., VOSNIADOU, S. and CARRETERO, M., Eds. (1999) *New perspectives on conceptual change*. Amsterdam, NL: Pergamon.
- SINATRA, G. M., and PINTRICH, P. R., Eds (2003) *Intentional conceptual change*. Mahwah, NJ: Erlbaum.
- STIGLER, J. W., GONZALES, P., KAWANAKA, T., KNOLL, S., and SERRANO, A. (1999) *The TIMSS Videotape Classroom Study. Methods and findings from an exploratory research project on eighth-grade mathematics instruction in Germany, Japan, and the United States*. Washington, D.C.: US Department of Education.
- STRIKE, K. A. and POSNER, G. J. (1985) A conceptual change view of learning and understanding. In L. West & L. Pines (Eds), *Cognitive structure and conceptual change* (pp. 259–266). Orlando. FL.: Academic Press.
- STRIKE, K. A., and POSNER, G. J. (1992) A revisionist theory of conceptual change. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 147–176). New York: State University of New York Press.

- THAGARD, P. (1992) *Conceptual revolutions*. Princeton, NJ: Princeton University Press
- TOULMIN, S. (1972) *Human Understanding: Vol. I*. Oxford: Oxford University Press.
- TREAGUST, D. F., HARRISON, A. G., VENNVILLE, G. J., and DAGHER, Z. (1996) Using an analogical teaching approach to engender conceptual change. *International Journal of Science Education*, 18, 213–229.
- TYSON, L. M., VENNVILLE, G. J., HARRISON, A. G., and TREAGUST, D. F. (1997) A multidimensional framework for interpreting conceptual change in the classroom. *Science Education*, 81, 387–404.
- TYTLER, R., and CONLEY, H. (2001) The science in schools research project: improving science teaching and learning in Australian schools. In D. Psillos, P. Kariotoglou, V. Tselves, G. Bisdikian, G. Fassouloupoulos, E. Hatzikraniotis & M. Kallery, Eds, *Proceedings of the Third International Conference on Science Education Research in the Knowledge Based Society. Vol. 1* (pp. 204–206). Thessaloniki, Greece: Aristotle University of Thessaloniki.
- VAN DER VEER, R., and VALSINER, J. (1991) *Understanding Vygotsky: A quest for synthesis*. Oxford, UK: Blackwell.
- VENNVILLE, G. J., and TREAGUST, D. F. (1998) Exploring conceptual change in genetics using a multidimensional interpretive framework. *Journal of Research in Science Teaching*, 35, 1031–1055.
- VON GLASERSFELD, E. (1989) Constructivism in education. In T. Husen & T. N. Postlethwaite, Eds., *The international encyclopaedia of education* (pp.162–163). New York: Pergamon Press.
- VOSNIADOU, S., and IOANNIDES, C. (1998) From conceptual change to science education: a psychological point of view. *International Journal of Science Education*, 20, 1213–1230.
- VOSNIADOU, S. (1994) Capturing and modelling the process of conceptual change. *Learning and Instruction*, 4, 45–69.
- VOSNIADOU, S. (1996) Towards a revised cognitive psychology for new advances in learning and instruction. *Learning and Instruction*, 6, 95–109.
- VOSNIADOU, S., IOANNIDES, C., DIMITRAKOPOULOU, A., and PAPADEMETRIOU, E. (2001) Designing learning environments to promote conceptual change in science. *Learning and Instruction*, 11, 381–419.
- WANDERSEE, J. H., MINTZES, J. J., and NOVAK, J. D. (1994) Research on alternative conceptions in science. In D. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 177–210). New York: Macmillan.
- WANG, M. C., HAERTEL, G. D., and WALBERG, H. J. (1993) Towards a knowledge base for school learning. *Review of Educational Research*, 63 (3), 249–294.
- WIDODO, A. and DUIT, R. (2002, June) Conceptual change views and the reality of classroom practice. Paper presented at the Third European Symposium on Conceptual Change. Turku, Finland.
- WIDODO, A., DUIT, R. and MÜLLER, C. (2002, April) Constructivist views of teaching and learning in practice: Teachers' views and classroom behaviour. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, New Orleans.
- WRIGHT, E. (1993) The irrelevancy of science education research: perception or reality? *NARST News*, 35(1), 1–2.