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REVIEW OF RESEARCH
Methods and issues of teaching and learning

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USING CONSTRUCTIVISM TO INFORM TERTIARY CHEMISTRY PEDAGOGY

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ABSTRACT: There have been many reports in the science education literature exhorting educators to teach from a constructivist view of learning. However, these reports typically fail to confront the difficulties associated with this stance. This review considers some of the implications and difficulties associated with a constructivist view of learning. The paper begins with an overview of paradigms and description of the origins of the constructivist paradigm that has become so dominant in science education research and scholarship, before discussing the principal criticisms of constructivism. The authors conclude that constructivism offers tertiary chemistry educators some valuable insights into classroom practice, but that appropriate pragmatism with regard to pedagogy is more important than adherence to any particular metaphysical belief system. [*Chem. Educ. Res. Pract. Eur.*: 2001, *2*, 215-226]

KEY WORDS: *alternative conceptions; constructivism; positivism; epistemology; ontology; paradigm; metaphysics; pedagogy; tertiary chemistry*

INTRODUCTION

There is a vast body of literature regarding students' views that are at odds with those of scientists and the intended teaching outcome (Pfundt & Duit, 1994, 1997). These discrepant views, known as alternative conceptions, may be environmentally derived from interaction with the physical environment or socially derived from interaction with family members, peers, or the media (Driver & Easley, 1978; Solomon, 1983; Taber, 2000). In some cases alternative conceptions are generated as a consequence of instruction; that is, given a problem to solve, the student may generate an alternative conception that seems to provide an appropriate solution (Osborne & Cosgrove, 1983). Such a situation is perhaps more likely in sciences like chemistry where students frequently encounter abstract concepts and contrived situations (Ben-Zvi & Hofstein, 1996). One of the most consistent and important findings of the science education literature is that alternative conceptions are robust and highly resistant to change (Banerjee, 1995; Barrow, 1994; Carmichael et al., 1990; Kogut, 1996; Nakhleh, 1992). Laws (1996) points out that the vast bulk of the alternative conceptions literature is concerned with secondary school science, with the literature for tertiary science education, such as it is, mostly confined to studies of newest undergraduates. It has been argued that that university educators do not take alternative conceptions research seriously, instead believing that it is only applicable to "extremely mediocre students" (Laws, 1996, p. 56). Recent work suggests that the alternative conceptions reported for secondary school and entrance level tertiary chemistry students are also prevalent for senior undergraduates and postgraduates (Coll & Taylor, 2001a,b). Such research begs the question as to the value of conventional instructional strategies for the teaching of counter-intuitive scientific concepts. Many in the science education community believe chemistry instructors need to be more aware of current learning theories as they seek to uncover truth and to impart this to students (e.g., Kettle, 2001; Taber, 2000, 2001; Tsaparlis, 2001).

In 1954 Albert Einstein stated, "it is difficult to attach a precise meaning to the term *scientific truth*" (p. 261). Our views of truth, and how we might discover it, represent part of our individual beliefs. Indeed, to infer that we can 'uncover' truth suggests a particular belief system, that is, belief in an objective reality (Von Glaserfeld, 1989b). Currently, one particular belief system, known as the constructivist paradigm, is dominant in science education and there have been numerous reports in the education and science education literature supporting constructivist-based teaching (see, e.g., Bell, Jones & Carr, 1996a,b). However, many articles supporting constructivist-based teaching fail to point out that constructivism has been subject to criticism (Coll & Taylor, 2000). Consequently, in this article we discuss some of the criticisms of constructivism. It is worthwhile to note at this point that a plethora of beliefs are routinely lumped together under the umbrella term *constructivism*. Despite this, there is little argument about the fundamental tenants of constructivism and so for the purposes of simplicity we use the term without modification. Before discussing some of the criticisms of constructivism, we describe the basis of paradigms and the salient features that are common to the various forms of constructivism. We conclude by relating our thoughts on what implications constructivism holds for pedagogy in chemistry; our focus in this article is on the perspective of chemistry educators at the tertiary level.

PARADIGMS AS BASIC BELIEF SYSTEMS

A paradigm is a set of basic beliefs (also referred to as metaphysics) that is concerned with ultimate or first principles and represents an individual's worldview. As such, a paradigm defines for the holder a view of the nature of the world, the individual's place in it, and the relationships between the individual and the world and its parts (Guba & Lincoln, 1989). Alternative paradigms include positivism, post-positivism, critical theory and constructivism. These belief systems are essentially acts of faith and it is important to realize that no paradigm is or can be considered incontrovertibly right. As Guba and Lincoln put it "advocates of any particular construction must rely on persuasiveness and utility rather than proof in arguing their position" (p. 108).

Paradigms consist of three features: *ontology*, *epistemology* and *methodology* (Cohen & Manion, 1994; Lincoln & Guba, 1985; Patton, 1990). The question as to what is the form or nature of reality or what is there that can be known is referred to as ontology (Chinn & Brewer, 1993; Denzin & Lincoln, 1998; Leplin, 1994). Two views of looking at reality have been identified by Cohen and Manion (1994) who ask: "Is reality external to individuals – imposing itself on their consciousness from without – or is it the product of individual consciousness?" (p. 6). The traditional scientific belief is that of a *realist* ontology; its adherents believe there is a single independent reality that exists outside the reference frame of the observer (Boyd, 1994a). This reality is immutable and conforms to natural laws—many of which possess the nature of cause and effect. At the other end of the spectrum is the *relativist* ontology; this asserts that there exist multiple, socially constructed realities. In the relativist view, there is no causal relationship, and mental construction precedes observation (Boyd, 1994b).

The relationship between the knower and the known is the question of epistemology. Guba and Lincoln (1989) state that epistemology is the pursuit of an answer to the question, "how can we be sure we know what we know?" (p. 83). It is generally held that an individual's epistemological views are dependent on their ontological views. According to Cohen and Manion (1998), if one subscribes to realist ontology, one is likely to be *objectivist* in epistemology, "a view that knowledge is hard, objective and tangible will demand of researchers an observer role" (p. 6). The principal alternative to objectivism is a *transactional, subjectivist* epistemology that holds that the findings of an inquiry are quite literally created by the investigator (Linn, Songer, & Lewis, 1991). In the words of Schwandt (1994): "What we take to be objective knowledge and truth is the result of perspective. Knowledge and truth are created, not discovered by mind" (p. 125).

Methodology addresses the issue of how we go about finding out whatever it is that we believe we know or can come to know (Guba & Lincoln, 1989; Schwandt, 1994; Guba & Lincoln, 1994). The answer to the methodological question is dependent upon an individual's stance on the ontological and epistemological questions. For example, those subscribing to realist ontology and objectivist epistemology rely on inquiry that is experimental and manipulative, in which questions or hypotheses are stated and are evaluated by empirical testing. In this approach careful control of experimental conditions is necessary to prevent outcomes being subject to extraneous influences. The contrasting position based on relativism accepts the subjective nature of inquiry.

The above descriptions of positivism and constructivism represent opposite ends of the metaphysical spectrum so to speak. There are naturally other belief systems and, for example, most modern realists would distance themselves from positivism by accepting at least some of the following theses: underdetermination of theory by evidence (the Duhem-Wuine thesis), and the theory ladeness of observations (Laudan, 1996).

THE ORIGINS OF THE CONSTRUCTIVIST PARADIGM

The beginning of the twentieth century was characterized by dramatic advances in modern physics, particularly in relation to atomic structure, the nature of electromagnetic radiation and gravity (Jones, 1994; Redhead, 1994). New theories such as quantum mechanics and relativity assumed the nature of interpretative multiplicity; the "failure of any one interpretation to provide an 'explanatorily satisfactory' link between the mathematic formalism and the world of laboratory experience" (Jones, 1994, p. 281). This particular thesis in relation to interpretative multiplicity is primarily attributed to the Copenhagen interpretation led by Bohr, Heisenberg and colleagues; in addition, there were some alternative interpretations led by Einstein, Schrödinger and so forth (Goldstein, 1996; Lakatos, 1970). Nonetheless, these changes in scientific thought began to undermine the conventional positivist belief that science could make absolutist claims. Philosophical, psychological, and logical arguments began to accumulate against the possibility of ever confirming or proving knowledge and ultimately led to the development of the constructivist paradigm (Nussbaum, 1989).

Wheatley (1991, p. 10) sums up the fundamental basis of constructivism:

> The theory of constructivism rests on two main principles. The first principle is readily agreed to by most persons but the second causes much controversy. Principle one states that knowledge is not passively received, but is actively built up by the cognizing subject. Ideas and thoughts cannot be communicated in the sense that

> meaning is packaged into words and 'sent' to another who unpacks the meaning from the sentences. That is, much as we would like to, we cannot put ideas in students' heads, they will and must construct their own meanings. Our attempts at communication do not result in conveying meaning but rather our expressions evoke meaning in another, different meanings for each person. Principle two states that function of cognition is adaptive and serves the organization of the experiential world, not the discovery of ontological reality...thus we do not find truth but construct viable explanations of our experiences.

Across all variants of constructivism there is consensus about the fundamental basis of the paradigm; that is, an individual's knowledge represents a mental construct. Typically constructivists ascribe to a relativist ontology, and a subjectivist epistemology and methodology, although there is disagreement about some aspects of constructivism, as Wheatley has stated, and we discuss this in more detail below.

CONSTRUCTIVISM AND CHEMISTRY PEDAGOGY

What does adherence to a constructivist paradigm mean for chemistry pedagogy? Acceptance of constructivist beliefs about the nature of truth and means of knowledge acquisition, results in a significantly different view of how one would teach chemistry (or other disciplines) (Matthews, 1997a, 1995, 1998; Taber, 2000). Inherent in a constructivist approach to learning is a shift away from the conventional positivist proposition based on a realist ontology in which science is seen as a codified body of knowledge that can be *transmitted* to the learner. From a conventional teaching point of view, students are seen to possess little, if any, prior knowledge of the concepts that they are required to learn, particularly for abstract scientific concepts (Cobern, 1993). Constructivists, in contrast, attempt to foster active learning, guiding learners to create their own constructs using a process of peer and teacher-facilitated learning (Driver, 1989a,b; Driver & Oldham, 1986; Wheatley, 1991).

Under constructivism, the teacher holds a totally different role; that of a facilitator rather than transmitter of knowledge. What pedagogical skills do tertiary chemistry teachers who wish to teach from a constructivist informed pedagogy need? Hand and Vance (1995) identify three new pedagogical skills that a constructivist teacher requires: negotiation, group work, and thinking on your feet. Unlike secondary school teachers, the latter skill is already quite familiar for many teachers in tertiary education and represents common teaching practice: the former skills are typically much less familiar.

CRITICISMS OF CONSTRUCTIVISM

Constructivism has come to dominate both thought and process in education and science education (Fensham, 1992; Matthews, 1998, 2000). However, the wide acceptance of constructivism by the science education community does not mean that its position has been unchallenged or taken on board by science teachers (see, e.g., Matthews, 1993, 1995, 1997b, 1998; Osborne, J., 1996; Osborne, R., 1993; Sutching, 1992). The rise of constructivism has been dramatic, but such success is potentially detrimental to reasoned debate since a mature, well-established paradigm tends to abrogate all avenues of research into itself and Solomon (1994) reminds us "no single perspective is ever likely to provide a final description of science education" (p. 17). The criticisms of constructivism in the literature can be broadly classified as concerns with the theoretical and philosophical basis, particularly its epistemology, and concerns with its pedagogical value.

THEORETICAL CONCERNS WITH CONSTRUCTIVISM

Constructivism has been criticized as portraying the individual as sealed in a privately constructed world in which the social component of learning is largely ignored (Davson-Galle, 2000; Ernest, 1993; Garrison, 2000). Likewise, it has been asserted that language and shared-meaning are largely ignored by constructivists (Ellerton & Clements, 1992; Sutching, 1992). Constructivists claim, "meanings cannot be shared in the sense that individuals construct identical meanings" (Hardy & Taylor' 1997, p. 142), a contention many authors dispute (e.g., Strike, 1987).

It is common for science education authors to assert that scientists hold positivist beliefs, although there have been few studies that have attempted to uncover scientists' metaphysical beliefs (see, however, Glasson & Bentley, 2000). In contrast, variants of constructivism seem to assume dual ontological positions. Constructivism appears to require a relativist ontology; however, some constructivists seem to assume an ontologically neutral stance, not dissimilar to that of positivism (Von Glasersfeld, 1989a). Similar criticisms have been levelled at constructivists' epistemological views, Kelly (1997), for example, argues that constructivism "straddles an epistemological divide from a Cartesian metaphysics to a social view of knowledge transmission" (p. 356) (see, also, Bickhard, 1997). The origins of this confusion lie in the lumping together of the different forms of constructivism and these versions hold significantly different epistemologies (Good, Wandersee & St Julien, 1993; Matthews, 1992). Although some constructivist authors criticize positivism on the basis that since science is a social construction, it incorporates bias and ideologies, such a stance is not necessarily inconsistent with positivism. As Kelly (1997) sees it, "because scientific knowledge is factual…, biases represent a problem with scientific methods (something to watch out for), but not scientific knowledge" (p. 360). In other words, ideologies are inevitable in human inquiry, but this is insufficient to claim that there is not an independent reality.

Recent work has suggested that there are number of underlying assumptions of constructivism that may not be supported by evidence or at least are open to alternative interpretations. Constructivism (and some other theories of teaching and learning) contains an assumption that human cognition depends on domain-free, general-purpose processing by the brain. However, this assumption is inconsistent with studies of children's early learning that suggests cognition is modular in nature (Matthews, P.S.C., 2000). For example, children learn language(s) rapidly and with little difficulty, compared with science. The argument is that language learning and ability of children to assimilate complex rules of grammar without teaching and apply them, is at least as complex as the learning of science.

In summary, critics of constructivism believe that the ontological and epistemological picture is muddled and lacking a coherent view, as some constructivists argue against realism, whereas others appear to argue that constructivism is a form of realism.

PEDAGOGICAL CONCERNS WITH CONSTRUCTIVISM

Rowlands (2000) claims that Vygotsky (a founder of constructivism) sought "to provide practical solutions to problems in education and yet no teaching strategy was made apparent" (p. 562). In other words, some critics of constructivism believe that pedagogy does not directly flow, or is not directly prescribed by constructivism. It is not in fact apparent that this is the case. For example, Matthews (2000, p. 497) asks, "is there a constructivist pedagogy? It is not clear that there is any specifically constructivist teaching method," but goes on elsewhere to argue “a constructivist pedagogical regime where pupils are respected, ideas are debated, and experiences shared, does not at all uniquely presuppose constructivist epistemology” (Matthews, 1997b, p. 308). Likewise, some authors do not accept that a realist ontology prescribes a transmissive teaching approach (see, e.g., Nola, 1997). Nonetheless, most researchers in the science education community hold that there is a constructivist pedagogy based on the ontological and epistemological assumptions described above (Driver & Bell, 1986). A constructivist-based model of teaching involves “elicitation of prior ideas, their clarification and exchange within the class group, exposure to conflict situations and construction of new ideas, followed by review of progress in understanding” (Millar, 1989, pp. 588-589).

Two major concerns with a constructivist-derived pedagogy have been posited. One is the fact that the implementation of such pedagogy is highly problematic, given large class sizes and the requirement to cover a detailed curriculum in limited time. Elicitation of student’ views, group work and so forth, all take time and this inevitably means less content is covered (Eylon & Linn, 1988). However, by far the major concern is the link between ontology/epistemology and pedagogy. In the first place, opponents of constructivism argue that relativism is not necessary to explain multiple theoretical systems. Kelly (1997), for example, argues that “reasonable realists do not deny that multiple theoretical systems explain empirical data” (p. 362), but does not believe that such multiplicity prescribes a relativist ontology. The danger in relation to pedagogy is that such stance makes it problematic for teachers to debunk scientifically dubious theories. Such a view would, for example, necessitate ascribing creationism and evolution comparable status. Irzik (2000) suggests that constructivism would mean “we start teaching N-rays after X-rays, creationism next to Darwinian evolution, and witchcraft and voodoo magic alongside Newtonian mechanics” (p. 635). Constructivism seems to infer the sole grounds for accepting a theory is viability; however, viability is inadequate as a criterion for truth (Nola, 1997). Other factors are of equal importance: empirical adequacy, theoretical plausibility, logical consistency, and potential fruitfulness for further research (Shulman, 1998).

Nola (1997) believes that a relativist ontology does not do justice to the extraordinary successes of science and undermines the traditional role of the teacher; that of an expert instructor charged with conveying knowledge based on his or her own learning and experience to novice students in the classroom (see, also, Matthews, 1997b). The problem is exacerbated by the fact that the science content taught at the high school and introductory tertiary level, represents knowledge about which there is little disagreement within the scientific community (Millar, 1989). The danger with a relativist stance is that it means teachers would treat good, solid, highly verified science as tentative, purely because it cannot ever be ‘proven’. But, as Kragh (1998) points out, even though a scientist is not divorced from his or her observations, this does not make scientific conclusions tentative; and from a practical teaching point of view, such a soft stance may introduce uncertainly about scientific findings that is quite unwarranted. Harding and Hare (2000) point out that the validity of scientific theories is based on a considerable body of evidence and for a teacher to infer that scientific knowledge is tentative is misleading: “It is certainly not so tentative that a student can come along with a little knowledge about the subject and only one piece of evidence, and make valid decisions about it” (p. 233). Science is made from creative acts done by fallible humans, and careful, controlled procedures do not automatically yield general conclusions and conclusions do depend on how the evidence is interpreted. However, the more evidence supporting a conclusion (especially evidence from varied sources), the more confidence one can have in the results. The ultimate arbiter of truth, as Bianchini & Colburn (2000) see it, “is consensus anchored in evidence and the accuracy of predictions based on conclusions” (p.

177). Thus, the validity of scientific conclusions should ultimately be based on evidence, paying attention to how it was generated, rather than on concerns as to how we could ever prove something to be incontrovertibly correct (Cobern, 1993).

Following on from the argument regarding the reduction in status of scientific achievements noted above, much criticism of constructivism has centred on the status given to students' views in the classroom, what some authors have even termed 'children's science' (Bell, Osborne & Tasker, 1985). But Jenkins (2000, p. 607) asserts: "Students' ideas about natural phenomenal are too glibly described as 'theories'."

In summary, critics of constructivism believe that relativist stance held by most adherents of constructivism undermines the successes of science and the role of the teacher, partly because it affords students' views too much importance.

USING CONSTRUCTIVISM TO INFORM TERTIARY CHEMISTRY PEDAGOGY

It is interesting to consider Einstein's thoughts about science teaching. Einstein (1954) believed teaching of science should serve more than narrow goals of producing graduates with clearly defined skills: "The aim [of instruction] must be the training of independently acting and thinking individuals" (p. 60). He saw as a key role of the teacher that of motivating students: "The most important motive for work in the school and in life is pleasure in work, pleasure in its result, and the knowledge of the value of the result to the community. In the awakening of and strengthening of these psychological forces in the young man [sic], I see the most important task given by the school" (p. 62). It is our view that a highly competitive classroom environment, based on a positivist view of science and transmissive model for instruction, does not foster such objectives. Matthews (1997b) argues, "One might reasonably ask whether learning theory or ideology is simply getting in the way of good teaching. Why must learners construct for themselves the ideas of potential energy, mutation, linear inertia, photosynthesis, valency, and so on? Why not explain these ideas to students, and do it in such a way that they understand them?" (p. 13). Indeed why not? We think this is so because no one seems to know how to accomplish this for complex scientific concepts. The plethora of studies into students' understanding of abstract scientific conceptions has suggested that conventional transmissive teaching does not (Pfundt & Duit, 1994, 1997). It seems to us untenable and simplistic to ascribe misconceptions of the extent reported in the science education literature on poor teaching, weak students or inattention.

Perhaps we are optimists, but it is our belief that the gulf between tertiary level chemists and teachers, and science education researchers is not as wide as it might appear based on the literature debates. Lawson (2000) states, "absolute truth about any or all ideas, including the idea that the external world exists, is unattainable" (p. 547) but goes on to point out "yet learning at all levels above sensory-motor requires that one assumes the independent existence of the external world" (p. 577). In other words, it doesn't really matter if you believe on a philosophical level whether there is a real, external world; there may as well be in purely practical terms. However, Kettle (2001), a highly experienced chemist and tertiary chemistry educator, recommends that chemistry educators need "a better in-depth insight into student understanding, learning and difficulties" (p. 6) and Tsaparlis (2001) likewise says, we can use whatever "theories and techniques" (p. 3) we find inform teaching. We don't think such advice should be lightly dismissed, but agree with critics of constructivism and other chemistry educators that one should employ the most appropriate tools, theories, or pedagogy appropriate to the educational context (Georgiadou & Tsaparlis, 2000; Matthews, 1997b; Zarotiadou & Tsaparlis, 2000). It is our assertion that tertiary educators need to be aware of ideas and issues raised by debates such as we have described in the paper, since these ideas can provide clues as to why their students hold views that are in disagreement with desired teaching outcomes.

Matthews (2000, p. 497) maintains that "most constructivists do not take the non-transmission thesis seriously, they do not let it get in the way of good teaching." Taber (2001) agrees, suggesting that constructivists are actually more pragmatic than much of the science education rhetoric might suggest: "Most constructivists working in science education take a more pragmatic stand: learners' alternative conceptions and frameworks are of importance because of their significance in the learning process: not because they are equally valid alternative views of the world" (p. 44). We concur and think that constructivists should admit that they are not purists who debate and discuss every concept with their students, but sensibly use the rich data gathered from constructivist-based inquiries in science education to inform their pedagogy.

So what pedagogy do we use in our classrooms, and how has constructivism informed our teaching practice? In our experience, the teaching of simple factual material *is* effective by conventional transmissive means and we believe that there is little to be gained by changing this teaching approach. We can see little point in trying to elicit prior knowledge or negotiate understanding of substantial parts of chemistry, like descriptive organic and inorganic chemistry. The effective teaching of challenging conceptions such as atomic structure and chemical bonding we believe, however, may be enhanced by a constructivist derived pedagogy. It is important to note at this point that there are other factors that make understanding of abstract concepts difficult for students, such as Piagetian level of the students (Lawson & Renner, 1975; Novak, 1978) and working memory capacity (Stamovlasis & Tsaparlis, 2000). Nonetheless, our tutorial classes are small, less concerned with content than understanding, and thus well suited to interactive constructivist-based strategies for appropriate concepts (Coll, 1997a). Specific tools we have used include elicitation or prior knowledge and probing of understanding via such techniques as *Predict Observe Explain* (POE) (White & Gunstone, 1992) and the use of concept maps (Sisovic & Bojovic, 2000). We also have found that POE also works well in large-lecture settings. Likewise, we have found success with the use of interactive group work, off-site learning experiences and more student driven activities such as case studies of local industries (Coll, 1997ab; Coll & Taylor, 2001a,b).

In our view, the key to quality chemistry teaching at the tertiary level is the more holistic approach endorsed by Einstein. This means teachers must engage the students in the learning process by using "every teaching method that involves students in an active way in the learning process increases their positive attitude towards science" (Zarotiadou & Tsaparlis, 2000, p. 49). We think a constructivist pedagogy, sensibly implemented using the tools given above, achieves this aim.

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