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Exploring Student Learning From a Constructivist Perspective in Diverse Educational Contexts

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Invited Paper

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ABSTRACT

This paper discusses the nature of different types of research that can contribute to our understanding of learners' ideas and learning in science topics. The paper considers the limitations of different types of research, and the expectations placed on researchers in carrying out their studies. A distinction is made between the standards expected of work that offers new empirical findings, and the higher expectations for theoretical novelty when looking to publish studies in international research journals. The importance of studying learners' ideas in different educational contexts is considered, and it is suggested that being able to relate research findings to specific features of the cultural or educational context may increase the theoretical importance of research reports. The general principles discussed are illustrated in terms of a discussion of the author's own research.

Keywords: Learning In Science; Alternative Conceptions And Frameworks; Students' Ideas; Exploratory Research; Qualitative Research; Confirmatory Research; Research In Different National Contexts; Quality Criteria For Published Research.

INTRODUCTION

This paper explores aspect of research into learners' ideas in science, and the nature of the types of studies likely to be considered to contribute to a progressive research programme into learning in science (Taber, 2006a). In particular, the paper considers the contribution that research undertaken in different educational contexts can make towards our understanding of student ideas and learning processes.

1) Research into Learners' Ideas Seen As Part of a Coherent Research Programme

There is a considerable literature from around the world that reports on aspects of learners' thinking in most science topics taught in school and at college level (Duit, 2007). At one level such work has been considered to be akin to 'natural history': that is similar to the observations and collection of specimens of minerals and living things that was once a respectable way to make a living, and which remains a fascinating hobby for the young enquiring mind. The critics point out that such 'nature collecting', whilst inherently interesting, is hardly the basis for a science. Indeed, when seen in isolation, many of the reports of students 'misconceptions' do indeed seem to offer little more than interesting curiosities.

Of course the great successes of modern biology, very much a science, grew out of the groundwork done by generations of collectors and naturalists. Indeed two of the greatest collectors, Charles Darwin and Alfred Russel Wallace, drew upon their wide observations of nature to develop the single most important and integrating theory in the life sciences: evolution by natural selection. A similar point can be made in chemistry, where a great deal of descriptive study of natural substances provided the basis to move beyond alchemical ideas and early chemical notions such as phlogiston and affinity to the development of the modern science. Geology and astronomy offer further examples of modern sciences that were built upon extensive periods of observational work.

A similar process may be perceived in science education, with the 'collecting' of accounts of students ideas, variously labelled as misconceptions, alternative conceptions, conceptual frameworks, intuitive theories and the like (Abimbola, 1988), offering useful background for developing a science exploring learning and teaching in science (Taber, 2006b).

The claim that this area of work should be considered scientific is an important, if potentially misleading, one. It is important because it sets out expectations about both the conceptual basis of the field, and on how researchers in this field should proceed. However, this can be misleading because whilst research into learning and teaching in science is a scientific activity, it is part of the 'social' sciences, and it should not be judged against the standards of modern natural sciences (NRC, 2002; Taber, 2007). Advanced disciplines such as physics have a considerable head start on science education.

At least as significant is the nature of what is studied in science education: learning and teaching are highly complex and multi-facetted phenomena, making the work of modelling them extremely challenging (Taber, 2006a, 2007/2008).

2) The Constructivist Research Programme

Scientific research programmes develop from particular conceptual bases (Lakatos, 1970); and much of the research in the field of research into learning and teaching in science is underpinned by constructivist notions of learning (Bodner, Klobuchar, & Geelan, 2001; Driver & Bell, 1986; Mintzes, Wandersee, & Novak, 1998; Taber, 2000b; Yager, 1995). The constructivist research programme was in effect established by the publication of a number of extremely influential papers over a five-year period around 1980 (Driver & Easley, 1978; Driver & Erickson, 1983; Gilbert, Osborne, & Fensham, 1982; Gilbert & Watts, 1983; Osborne & Wittrock, 1983). In effect, these papers (and other similar publications by these and other authors) set out a 'hard core' (Lakatos, 1970) of assumptions about the nature of learning and teaching in science, and the purposes and possibilities for research. In retrospect is seems that the common central assumptions of the constructivist research programme can be summarised along the lines of the following points (Taber, 2006a, 2006b):

- Learning science is an active process of constructing personal knowledge.
- Learners come to science learning with existing ideas about many natural phenomena.
- The learner's existing ideas have consequences for the learning of science.

- It is possible to teach science more effectively if account is taken of the learner's existing ideas.
- Knowledge is represented in the brain as a conceptual structure.
- Learners' conceptual structures exhibit both commonalities and idiosyncratic features.
- It is possible to meaningfully model learners' conceptual structures.

Much of the research that has been undertaken since can be seen as a means of responding to the research questions suggested by these points. So one of the questions posed is 'What ideas do learners' bring to science classes?' A good many of the thousands of studies carried out by 'constructivist' science education researchers world wide in the past few decades can be seen to be addressing that issue (Duit, 2007).

However addressing that question *by itself* does not move the research programme beyond the 'nature collecting' stage. Other research questions need to be addressed for our research to usefully inform teaching itself (Taber, 2006a, 2006b). These will be questions such as:

- What is the nature of learners' ideas?
- How do learners' ideas interact with teaching?
- How should ('constructivist') teachers teach science?
- The challenge of contributing to the field

As science education has become a well-established field of scholarship, it has developed into a complex field, with an extensive literature that no one researcher can be expected to master. Constructivism has widely been considered to be the dominant theoretical position adopted by many researchers, but there have been a number of influential traditions (Erickson, 2000; Solomon, 1993), and different 'versions' of constructivist thinking even among the 'constructivists' (Bodner et al., 2001).

New researchers entering the field need to position themselves in terms of a currently acceptable approach informed by scholarship within the literature. The literature of science education is itself complex, drawing upon concepts and approaches from a range of other disciplines such as cognitive science, developmental psychology, social psychology, anthropology and the history and philosophy of science. These specialist areas each have their own specialist terminology, different taken-for-granted assumptions, and particular commitments - to the nature of the phenomena studied, and the forms of knowledge that are possible and should be sought.

Many researchers in science education are initially graduates in a physical or life science discipline, and so may find the literature in the behavioral and social sciences very unfamiliar. This is a particular challenge for those who are reading this literature in a second language. Science education as a field falls under the social sciences, and natural scientists who wish to become educational researchers need to undergo a significant professional shift (Kind & Taber, 2005) in trying to understand the rather different assumptions of their new field.

One man who successfully made a similar transition was physicist-cum-historian of science Thomas Kuhn. Kuhn presented a very influential model of how professional scientists are initiated into their research field (Kuhn, 1996). Typically this professional education involves specialist research training and doctoral research undertaken in an established research group, under the guidance of an experienced expert supervisor in their field; and then post-doctoral work with further more advanced mentoring within an active research group. This model of specialist research training and cognitive apprenticeship

(Hennessy, 1993), is certainly how new science education researchers are prepared in those countries with well established traditions in science education research.

Making this transition is much more difficult in a context where the expertise is not available, and where those who took their doctorates in high energy physics, organic synthesis, or plant genetics may be assumed to have the research skills to begin enquiries in a very different research field. This is unrealistic when expertise in any field typically takes at least of decade of hard work (Gardner, 1998). A doctorate based on developing a novel application of nuclear magnetic spectroscopy does not prepare a researcher to use ethnographic methods to investigate the nuances of students' thinking!

3) Types of Methodology

This is not to suggest that there is no overlap between the methodologies used in natural science and educational research. Some research in science education relies on similar statistical techniques to those used in many natural science investigations. However, a broad spectrum of techniques is used in science education research, and some are more familiar to the natural scientist than others. Moreover, these different research methods are not used interchangeably, and journal referees and editors expect to see that the choice of techniques is based on reasoned and principled match of methodology to research question (Taber, 2007). This is a point that will be illustrated later in the paper.

A rather simplistic caricature of extreme approaches used in science education research would be experimental studies at one pole, and interpretive interview studies at the other extreme (Gilbert & Watts, 1983; Taber, 2007). Researchers new to the field, with natural science backgrounds, may be inclined to prefer the experimental approach, as this is more familiar from their scientific training.

4) Difficulties with Experimental Design

The research design is in principle very simple: a comparison is made between an experimental group, subject to some teaching intervention or similar, and a control group that is all other senses identical. However, in practice no control group in education can ever really be considered to be identical, so a good match is sought. But the list of possible variables that might need to be controlled can be unwieldy.

- Does the control group need to be matched for size – exactly?
- What about gender composition?
- Perhaps 'intelligence' (if we can agree on what that is), or prior attainment in the subject should be matched?
- Perhaps we should se a pre-test to establish that the groups start off with similar understanding of a topic – but how similar does this need to be?
- Do we need to match the groups for interest in the topic? Or general motivation in science lessons?
- Should both classes be taught by the same teacher? In the same classroom? At the same time of day?

Of course it is possible to design research along these lines by making informed decisions about such matters, but it is no simple matter. Consider some of the complications that have to be taken into account. Firstly, in physical science we can often test the same sample in different conditions, which saves having to find a matched sample. This does not work with learners – as there is a mental hysteresis effect (i.e. learning!) that means we can not bring our 'subject' back to the initial conditions before our test. Sequential 'conditions' will therefore have effects that interact. For example, higher scores on a post-test could always just be an effect of having taken the pre-test and may have occurred without *any* teaching input.

As an example of this, a Physics professor in the US has described how teachers responded to two workshops on successive days relating to teaching about floating and sinking (Cromer, 1997). The first workshop was based on practical work with a 'discovery learning' feel, and the second was a longer compound session including debate, demonstrations, practical work. Cromer reports that when the teachers were asked about the workshops later they commonly felt that the practical session was more fun, but that they learnt more from the second approach. This may well have been the case, but without a comparison group where the sequence was reversed it is difficult to know to what extent the experiential learning in the first workshop help prepare the teachers to learn from the later presentation. Cromer does not claim this episode was set up as a research study, but as he clearly wishes to use the data he collected to make a knowledge claim – about the relative effectiveness of different types of teaching input – it is important for a reader to spot that his 'evidence' is anecdotal and was not systematically collected.

So we always have to compare with a different sample, but – as pointed out above – different samples of learners are not available in standard specifications in the way metal cylinders, or samples of chemicals, are.

Another complication, especially for studies taking place over extended periods, is that learners are subject to maturation effects. In other words, they might develop a better understanding of a topic without being taught about it as their thinking becomes more abstract and sophisticated (Herron, 1975). So 'gains' found over a unit, module or course may just reflect general cognitive maturation.

So in our experimental set-up we will be testing out a treatment on one group, and will have designed the control group to be as matched as possible. Both groups will be pre-tested, the treatment group will have the innovative teaching input, the control group will not, and both groups will be post-tested. If the pre-tests results from the two groups are considered close enough, and the post-test results sufficient different, we have an effect.

Yet we also have to consider what the control group is doing *instead of* having the treatment. If the treatment group receives some special teaching input and then out-perform the control group who have not been taught the topic at all, then all that has been shown is that *some* teaching is more effective than no teaching at all. Even very uninspiring and poorly structured teaching should produce that outcome. So instead the treatment is compared to another form of teaching. So often a new approach, perhaps a constructivist approach based on conceptual change theory (Posner, Strike, Hewson, & Gertzog, 1982; Wightman, Green, & Scott, 1986) and involving experiments, group work, discussion etc, is compared with a 'traditional' approach such as the teacher lecturing and students taking notes. This is clearly a genuine comparison, but there are still two sets of problems.

Firstly, any effect produced may have more to do with novelty than with teaching effectiveness. Sometimes learners lack confidence in a new approach, and may not respond well, especially if it does not look like 'proper teaching'. Conversely, if normal lessons are found a bit dull, anything new may raise interest and engagement. Findings here may not reliably indicate what long-term effects would be found if new approaches became the norm.

Secondly, research has shown that 'expectancy' effects are very common in contexts such as this (Rosenthal & Jacobson, 1970). If the researcher is positive about the treatment and expects a significant finding, it is more likely that one will be found. The mechanisms whereby researchers' own expectations are somehow transmitted to the subjects of an experiment are not always clear, but the evidence for an effect is robust. In medical research this is overcome with double blind methods: neither the researcher administering drugs, not the patients, know who is getting what. In teaching this is difficult: it is not possible to undertake a study without the teaching knowing which groups is getting the innovative treatment.

The science education literature certainly includes experimental studies that have been designed to address as many of these problems as possible. However, this brief discussion should offer some indications of the difficulty of convincing journal editors and referees that such a study has sufficiently dealt with the various issues to produce a meaningful comparison that reflects the merits of the treatment rather than some other extraneous factors. Alternative procedures for testing out classroom approaches are increasingly favored, approaches such as 'lesson study' (Allen, Donham, & K, 2004) or 'design experiments' (Brown, 1992).

5) Interpretive Research

Given the difficulties of experimental research it is often more feasible to undertake qualitative research based on interpretive methods such as interviewing (Bell, 1995). Much of the literature on learners' ideas in science is of this type. A basic approach involves the researcher interviewing a suitable group of learners and analysing their responses to interview questions. The outcome would be an account of students' conceptions (or mental models, etc.) about a particular topic.

In principle, the design of such studies may seem very straightforward, and indeed some of the early published accounts of students' ideas are written up as little more that a presentation of the ideas uncovered in talking to a convenient group of learners about some topic of interest. However, the researcher looking to undertake publishable work needs to be aware that the apparently simple nature of such research is deceptive (Watts, 1983). There are quite stringent quality criteria applied when evaluating qualitative studies in science education, distinct from those used to judge quantitative studies, reflecting the distinct nature of this type of research (Eybe & Schmidt, 2001). Here space only allows a brief comment on some of the issues that researchers should keep in mind.

6) Selecting a Focus and Justifying Research Questions

A key issue in any study is its conceptualisation: the conceptual framework that locates the study and offers the basis for identifying a research question that is worth answering (Taber, 2007). At the outset of the constructivist programme, the widespread adoption of key tenets such as 'the learner's existing ideas have consequences for the learning of science' and 'it is possible to teach science more effectively if account is taken of the learner's existing ideas' (Taber, 2006a), suggested that exploring students' ideas about a science topic was justified as long as the topic had not already been explored in that population. So knowing what seven year olds think about dissolving or what 17 year-olds understand about evolution could be useful in informing teaching.

In principle this rationale has not changed, except that there are now many studies already available in the literature reporting students ideas across a wide range of ages and topic areas. The researcher needs to find an unexplored 'niche' to be able to offer a new study as original.

However, given the vast literature on children's ideas in science, a study that is empirically novel, but theoretically uninteresting is unlikely to be accepted in a prestigious research journal. That is, given the high rejection rates of top journals, finding a new combination of student group and topic will not ensure work that can be published in the international research literature. Ideally a new study clearly has to offer useful theoretical development or critique as well as analysis of new data.

Consider, as an example, a key area of chemistry, that of chemical structure and bonding. Previous research (to be discussed further below) has shown that high school and college students commonly develop alternative conceptions in this topic area, which interfere with them learning the target knowledge presented in the curriculum. It has been suggested, for example, that UK students commonly develop a particular way of understanding chemical bonding described as an alternative conceptual framework (Taber, 1998a). Teachers have been advised to consider such findings in planning their teaching and to alter some aspects of the sequencing and presentation of the topic (Taber, 2001a).

Some of the findings from the UK research have been found to apply in a number of other countries (Tan et al., 2007). This might imply that the research is uncovering ideas that are readily accepted by humans - something about our intuitive ways of thinking about the world, e.g. (diSessa, 1993) – or may reflect common aspects of the way chemistry is taught in these different educational systems. (Of course, it could well be that both of these factors are operating together.)

It would be useful for teachers in, for example, Turkish schools and universities to know whether learners in that country tend to demonstrate similar alternative ways of thinking about chemical bonding. Turkish researchers may well decide to undertake studies to explore this issue, and if carefully carried out these studies could produce results that should be reported to inform Turkish practitioners teaching these groups of students. Certainly then such studies should be reportable in journals aimed at Turkish teachers themselves. However, if the findings are similar to those from studies previously reported in the research literature, then editors and referees of research journals may well take a view that the new studies offer little that is novel, and so cannot justify space in the international research journals.

Journal editors may adopt the view that that the field has moved beyond studies that would be considered largely ‘descriptive’ in merely filling in more detail of which students demonstrate which ideas about which topics. Researchers undertaking such work are doing a useful service to the educational community, but still may not find their work is readily published in international journals. Publication in the most prestigious journals is likely to depend upon offering something more to the research community.

A number of avenues of research have developed which move beyond simply identifying students’ ideas – for example looking at how ideas develop over time (Petri & Niedderer, 1998), how they interact with teaching (Duit, Roth, Komorek, & Wilbers, 1998), how they develop within a wider conceptual ecology (Taber, 2001b) and so forth – but these types of enquiries are more complex than studies focused on identifying alternative conceptions.

7) The Variable of Educational Context

One potential way to give a study into learners’ ideas a greater theoretical value is to look to link the findings to features of the educational context that may be of wider interest. Different educational systems may have different features that will influence student learning, and identifying these features and understanding their effects could well be of interest far beyond the particular focus of the study.

There are clearly many features of an educational system that could potentially be of relevance, including but not limited to:

- features of the language of instruction (such as idioms used in the subject)
- the age at which certain topics are introduced
- the sequencing of topics

- the teaching models and analogies, demonstrations or standard classroom practical work commonly used to teach particular ideas

An educational system is clearly set within a wider cultural context, and there may well also be important influences that arise out of school which are specific to some educational systems. A research report that offered illuminating insights into how such specific factors led to (or influenced the development of) particular aspects of the students' ideas has considerable potential to further our understanding of teaching and learning science.

8) Clarifying Theoretical Constructs

It is unfortunate that the literature on students' ideas includes a range of terms without any widely agreed relationship between them (Abimbola, 1988). Different researchers seem to mean different things by the same terms, and sometimes use different terms apparently synonymously. A researcher who simply acknowledges this, and then states that they chose to write about 'alternative conceptions' or 'mental models' will be expected to clarify what they mean by the term they have chosen, and why they favour it. Moreover, the research report needs to then be clearly consistent with the selected terminology.

As one example, the term 'misconception' is widely used and has the advantage that it is familiar to many classroom teachers (Taber, 2002b). It is therefore a suitable term to use when writing for practitioner journals (i.e. professional journals primarily read by teachers). Among researchers, however, 'misconception' is often considered to imply a simple misunderstanding of teaching, rather than something more fundamental and potentially having significance for learning (Driver & Easley, 1978). A misconception could easily be corrected through the teacher clarifying the misunderstood material. When reporting research undertaken in the constructivist tradition in academic journals, it is therefore usual to prefer a different term that is more in keeping with the theoretical stance of constructivism: alternative conception, or intuitive theory or mental model etc. However, these terms have been used in various ways, and it is important to offer a clear account of what a particular researcher means by such a construct.

The early constructivist research literature has been criticised for confusing the ontology of the entities being researched, something that makes for research that lacks rigour (Phillips, 1987). In part this may be seen to relate to how different early researchers decided to define their terms. So the common term 'alternative (conceptual) framework', for example, was used very differently by Driver and by Gilbert and Watts. Where Driver used the term to refer to the cognitive structures of individual learners (Driver & Erickson, 1983), Gilbert used the same term to refer to models built by researchers when representing common features of different students' ideas (Gilbert & Watts, 1983).

Clearly these are two very different types of entities. Driver's conceptual frameworks are an inferred aspect of a hypothetical unobservable: it is not easy to explain in what form such a thing actually exists except for what we infer to be *encoded in* brain circuits (Taber, 2007/2008). Gilbert and Watts however are referring to something very different– an expressed model presented in verbal and/or diagrammatic form (Gilbert & Watts, 1983). However it only represents the researchers' own mental models constructed from their interpretations of the comments of different individual learners.

This is not intended to criticise either of these uses of the term 'alternative framework', and it is just unfortunate that the same label was applied differently by different research groups. However, to misread a 'Gilbertian' conceptual framework as a 'Driverian' one would be to make a major category error. Elsewhere I have discussed the problems that making such an error can lead to (Taber, 2007). Here I merely point out that researchers need to be very clear about the meaning of their technical terminology.

9) Data Collection and Analysis

Research design clearly needs to be consistent with the research questions asked, and the way the research claims to conceptualise the field. There are a number of key issues that need to be considered at the point of designing a study, because they will inform all subsequent research decisions (including how to present the research report).

A key feature of interpretive research is how it uses in-depth methods to explore the nuances of an *individual'*s thinking, so that a model may be constructed of how the individual thinks about a topic. That is, such research takes an *idiographic* approach. Lengthy semi-structured interviews are a common approach, and these may include probes such as diagrams (Gilbert, Watts, & Osborne, 1985), demonstrations (Gilbert et al., 1982), concept maps (Rye & Rubba, 1998; Taber, 1994b), concept cartoons (Keogh & Stuart, 1999), or card sorting (Taber, 1994a) for example. Other types of data may also be used, such as observations of the student working, written work, classroom dialogue. The aim is to test out the meanings that the learner has for scientific concepts. So interviews need to probe – to check out the researcher's interpretations, to seek manifold conceptions or multiple framework of understanding (Pope & Denicolo, 1986), to test out the range of application that the student has for a concept.

This raises key issues of sampling. In-depth work is only feasible with a limited number of informants, and the level of cooperation needed from students may limit the pool of volunteers prepared to subject themselves to interrogation (Taber, 2002e). In general, interpretive studies compromise generalisability for authenticity. That is, research reports should be detailed accounts (Geertz, 1973), that give real insight into the thinking of learners, but may be based on a limited number of students who cannot be assumed to be representative of wider populations. This is a limitation, and means that this type of research is complemented by other approaches based on survey methods (see below).

Analytical approaches clearly need to match the density and detail of the data collected. The analysis of qualitative data is a skilled process that involves spending time working through and reflecting on the best way to reduce and model the data to reflect the students' own ideas. Idiographic research uses approaches that are designed to be as true to the data as possible, involving iterations of analysis that start with open coding (fracturing data according to the way the informant sees things), before slowly building up more general categories that abstract key features to build up a model for publication. This approach is based on the techniques developed in 'grounded theory' research (Glaser & Strauss, 1967; Taber, 2000a). However, reading of previous literature can offer useful insights into fruitful ways of fragmenting and understanding the data (Taber, in press).

10) Exploratory and Confirmatory Research

Of course not all research into learners' ideas in science is based upon in-depth explorations of a small number of informants, and often we are concerned with the aspect of the research programme (Taber, 2006a) that asks *how much commonality is there between learners' ideas in science?*

To answer this type of question we need to use survey approaches, where we sample a population to find out which proportion of the sample have certain ideas. Normally we intend the sample to represent a specific population – such as 16 year-old school leavers in England or trainee chemistry teachers in Turkey.

11) Sampling

There are various approaches to sampling populations. The most rigorous approach involves random sampling from the entire population (Assessment of Performance Unit, 1989), in which case statistical methods can offer an indication of how well the proportion of students demonstrating some idea in the sample should reflect the proportions that would be found in the wider population (e.g. the approach allows claims such as that is that there is a 95% likelihood of the population frequency being within ±2% of the sample frequency).

However, such approaches are not usually viable, especially for individual researchers or small research groups. Convenience samples are therefore often used, usually of groups of students to whom researchers have ready access.

There is nothing wrong with such an approach in principle, however it is important to acknowledge in reports that the weaker form of methodology has been used - as clearly a particular group of students from a particular town, or a class in one university, may not be typical of a national population. It is usual in such circumstances to offer as much context of the specific sample as possible in research to allow readers to make their judgements about the likely relevance of the findings for other contexts – i.e. what is called reader generalisation (Kvale, 1996; Taber, 2007).

12) Quantity versus Quality

Survey methods allow us to test out the commonality of aspects of learners' ideas, which is not possible with more qualitative approaches (where the in-depth nature of data collection and analysis makes working with large numbers of students non-viable). However, the gain in sample size comes at a high cost. Surveys are not able to collect open-ended data that might reveal idiosyncrasies of individual thinking. More over, there is little opportunity to uncover the fine-grained aspects of student thinking (Taber, 2007/2008) which are important in making sense of how learners ideas come about, develop, respond to teaching etc.

These approaches are therefore not suitable for *exploring* learners' ideas, but are best matched to research that looks to test out the frequency with which conceptions that have previously been detected have been found. This type of research is sometimes labelled as 'confirmatory' as oppose to 'exploratory' (Biddle & Anderson, 1986; Taber, 2007). Exploratory research is needed when we have limited understanding of a situation and are not sure of what ideas students in a group are likely to hold. Once we have undertaken sufficient exploratory research to carefully characterise students alternative conceptions and frameworks, we can then move on to 'confirmatory' research to test out how common these notions are. We do this by setting up test items specifically designed around known conceptions (Taber, 2002a).

These different approaches then may form part of a sequence of studies that fits within a research programme (NRC, 2002; Taber, 2007). In practice there are probably at least three steps in such a sequence (Taber, 2000a):-

Eliciting learners' ideas needs data collection and analysis techniques that are open-ended and which collect detailed data that can be carefully analysed in an interpretative mode, working with case studies of individual learners;

Identifying commonalities involves building models based on comparing and contrasting the findings from particular case studies;

Identifying common alternative conceptions requires survey type approaches using test items that are carefully written to reflect candidate conceptions identified in the earlier stages of the research.

Treagust has described in some detail stages in developing instruments to survey common ideas among student populations (Treagust, 1988), and a detailed account of the stages in developing one such instrument is given by Tan and colleagues (Tan, Goh, Chia, & Taber, 2005).

Sometimes researchers attempt to short-cut this process, by surveying classes in ways that do not offer satisfactory approaches for either exploratory or confirmatory research. To offer a caricature of how *not* to undertake research in this area, a researcher may seek to survey a class (such as university group) by setting them a small number of open-ended questions. This approach is not satisfactory for exploring in-depth student thinking, especially where there is no interactive component to explain and clarify the question, or probe and test out the student's response. Unlike interview responses, written responses offer no opportunity for clarification of the students' meaning - which is so important in making sense of how a learner thinks about a topic. Students, of course, often use technical scientific terms in very different ways to teachers and scientists (Watts & Gilbert, 1983).

The data collected in this way is therefore not suitable for in-depth interpretive analysis. Analysis therefore often proceeds by coding the responses against the expected target knowledge in the curriculum. However, there is no way to know if what is left unsaid is not known by the student (or just not included in the response), or whether an idea expressed is just one of a number of manifold conceptions held. The types of data collection approaches use methods very similar to assessments, where the aim is to test whether students can offer right answers, rather that research approaches suitable for 'getting inside' students' minds.

The findings are therefore frequencies of the researchers' interpretations of brief written responses into categories that have no demonstrated authenticity in terms of students' thinking. Whilst such results may offer some interest as provisional work, the lack of rigour of the approach used make it very unlikely the findings can be seen to offer authentic new knowledge of sufficient status to interest the editor of a research journal.

Careful work is therefore needed to select or develop instrumentation. However, as suggested above, even when surveys use instruments pre-tested in previous research, or carefully developed by the researchers themselves, there is no guarantee of outcomes that are publishable. If findings are clearly at odds with published findings, this might be considered of interest, but more subtle discrepancies are only likely to interest journal editors is the findings can be clearly linked to the special features of the particular educational context, e.g.

> …previous research was undertaken with school age students, and the present research was undertaken with university students who had studied more advanced models of the atom: it is interesting therefore that we found strong similarities with the previously reported findings…
>
> …unlike in countries where the previously cited research was carried out, in the present educational system the 'particulate nature of matter' is not studied until after students have completed an extensive course of descriptive chemistry encompassing states of matter, acids and alkalis, dissolving, extracting metals, combustion and a number of other topics. It is interesting therefore that …

13) An Example of an Individual Research Programme

The previous sections of this paper have set out some of the key features, and limitations and challenges, of different types of research that can contribute to our knowledge of students' ideas and thinking in science. Some of these themes will now be illustrated through a particular example.

In the author's own research - mainly from working with students in England (in the UK), and particularly with 16-19 year old college students - I have particularly looked at aspects of learners' understanding of basic chemistry topics such as bonding, structure and the how chemical reactions are understood at the sub-microscopic level. This is the realm of 'quanticles' (Taber, 2005) – atoms, molecules, ions, electrons etc: entities we sometimes confusingly refer to as 'particles', although they are not like the particles of dust, salt, sand etc. that learners are familiar with. It is well known that the widespread reliance of quanticle models as the explanatory basis of much of chemistry offers a major challenge to many students (Taber, 2001a). The work discussed here has been reported in more detail in a range of published reports, and readers interested in this specific topic area are referred to those papers (Taber, 1995, 1997, 1998a, 1998b, 1999, 2000a, 2000c, 2001b, 2002c, 2002d, 2003b, 2003c, 2005, Accepted for publication; Taber & Coll, 2002; Taber & Tan, 2007; Taber & Watts, 1996). Here my concern is to highlight some general features that may be of value to researchers looking at student thinking and learning in any science topic – and in particular those researchers who are relatively new to educational research.

- Aspects of student thinking uncovered in these studies included:
- Everything is made from atoms, so reactions occur between atoms;
- Atoms or ions with full shells are always stable;
- Atoms spontaneously ionise to obtain full shells;
- When an electron is removed from an atom, the remaining electrons take up its share of the nuclear force;
- Reactions occur so that atoms can get full electron shells (implying reactants are not composed of species with full shells);
- Atoms actively seek (want, need) full shells;
- Bonding allows atoms to get full electron shells;
- There are two main types of bonding, based on sharing electrons to get full shells, or transferring electrons to get full shells;
- Sharing an electron allows it to fully count as part of both atoms involved;
- When a covalent bond breaks, each atoms gets its own electron back;
- Ionic material exists as molecules made up from atoms that have been involved in electron transfers;
- Forces between ions that have not exchanged electrons are not ionic bonds, but just forces;
- Atoms can only form as many ionic bonds as they can donate or accept electrons;
- Double decomposition reactions involve electrons being returned to their original atoms before new electron transfer events can form new ionic bonds;
- Metallic bonding is a kind of bonding because it lets atoms get full shells in similar ways to covalent/ionic bonding;
- Polar bonds are basically a subcategory of covalent bonds that have been distorted;
- Forms of 'bonding' that do not enable atoms to get full outer shells, such as 'hydrogen bonding' are not really bonds, but just forces;
- Electron orbitals are trajectories like orbits;
- Resonance structures alternate in actual molecules;
- Benzene molecules have spare electrons kept inside the ring;
- Electrons spin like spinning tops.

Clearly students tend to think about the nature of quanticles and the processes of chemistry at the sub-microscopic level very differently from chemists! For the purposes of the present paper I would like to briefly mention a few point about this research to link it with the general points I have made above about suitable approaches to researching student ideas.

One of the main outcomes of the research was an alternative conceptual framework for how learners understood the area of chemical bonding (Taber, 1998a). For my own work I adopted the Gilbert and Watts (Gilbert & Watts, 1983) use of the term 'alternative framework' – that is I used this term to refer to my model of generalities across student accounts, rather than to describe the thinking of individuals. The frameworks included a range of discrete conceptions (relating to the points listed above) that seemed to be linked in students' thinking. However no one individual learner necessarily fitted the full framework: it was, rather, a model illustrating a set of linked ideas, each of which seemed to commonly feature in students' comments and explanations.

Before reaching the stage of producing the alternative framework, then, I had been working at exploring the learning of the different students on an individual level, based on sequences of in-depth interviews. This allowed me to develop case studies of the accounts of individual learners. The use of lengthy detailed interviews provided opportunities to test out students' meanings as suggested above. This is especially important when the researchers would not have considered the students' way of thinking, and so may easily misinterpret it. So in depth analysis of my interviews with Annie revealed an idiosyncratic alternative conception of the meaning of ionic charge (Taber, 1995). Of course a case study does not offer any generalised findings. This alternative conception was highly significant for Annie's own understanding of some aspects of chemistry, but did not appear to feature among the thinking of any of the other students I worked with.

But case studies allow a depth of enquiry that is necessary to explore aspects of students' learning. For example, extended sequences of (over twenty) interviews with one of my informants allowed investigation of how his ideas changed over time. By interviewing him in depth it was possible to identify that Tajinder held manifold conceptions relating to why chemical reactions occurred – he used three different explanatory principles that seemed largely discrete in his thinking (Taber, 2000c). This would not have been spotted using more limited data collection techniques. For example, a written questionnaire would probably only have elicited one his explanatory principles as Tajinder tended to produce an explanation that he felt was most viable for a particular reaction. Only by asking him about a wide range of examples were his manifold conceptions identified.

As Tajinder was studied over an extended period, and in depth, it was possible to see how his thinking changed, and so to link this with the wider context of shifts in his 'conceptual ecology' (Taber, 2001b). By re-interviewing Tajinder several years after he completed his chemistry course, it was also possible to identify which of his ways of thinking about the subject were more readily accessed and which had in effect been forgotten (Taber, 2003a).

Case studies then offer insight into features that can only be understood by extended and careful close study. Any individual researcher can only expect to work on a limited number of cases in any depth at one particular time, as such enquiry is time-consuming. Using case studies to model more common features is therefore likely to be based on moderate sample sizes (Taber, 1998a, 2005), and cannot offer strong generalisability.

This is where survey approaches become useful. Once potentially common alternative conceptions have been identified it is possible to design instruments that can be used either to survey them in broader populations. Where significantly high frequencies are found among larger samples, then it may be possible to devise diagnostic tools to help classroom teachers identify alternative conceptions in their own classrooms (Taber, 2002a).

Here it will suffice to offer a single example. The ion Na^{7-} is one that would only be expected to exist under very extreme conditions, and is certainly unfamiliar to students at school and college levels. Yet comments from students interviewed in depth suggested they thought that any species with an octet of electrons or full shell would be stable. This finding informed some of the items included in a survey instrument, the Truth about Ionisation Energy Instrument. This was a simple tool that presented statements for students to judge as true or false. It was not able to facilitate the exploration of student thinking in depth, but did allow data to be collected quickly from larger numbers of students. The use of a confirmatory approach was here justified by the earlier interpretative work that had used an exploratory approach to elicit learners' ideas in their own terms (NRC, 2002; Taber, 2007).

A survey within a single English college found that 83% of students (91/110) agreed with a statement "the [sodium] atom would become stable if it either lost one electron or gained seven electrons" (Taber, 2000a). A subsequent study based on a larger, more heterogeneous sample made up of students from 17 UK institutions found a very similar proportion of respondents (83%, 274/330) agreed with the statement (Taber, 2003c). A different instrument asking students to compare different chemical species was used with smaller samples and it was found that most of each sample (21/29; 17/19 and 21/33 – overall 73%) judged a sodium atom to be less stable than the Na^{7-} ion (Taber, Accepted for publication). As none of the samples used in these studies were based on random or representative sampling of larger populations, the percentage figures quoted only give indications of how frequent this conception would be in the wider population. However, in view of the potential significance of the finding (in terms of the models taught in chemistry), and the high levels of students rating Na^{7-} as stable, the results are important enough to be reported in the literature.

DISCUSSION

Having offered an example of how different forms of research may feature in an individual's research programme, I will now briefly turn to the question of how published research can inform new studies in less well studied educational contexts. As this paper was invited for the *Journal of Turkish Science Education*, I will assume that the hypothetical new research will be carried out in Turkey.

Consider our example of research into learners' ideas about chemical bonding and related topics. Given that this has led to some interesting findings from English students, it might well be a focus of interest in other educational contexts. There are a number of approaches that could be taken in a study that looked to explore how Turkish high school students understood chemical bonding, and I will briefly consider a few examples to illustrate some important distinctions.

Consider these possible research foci:

a) What proportion of Turkish high school students conceive of ionic bonding in terms of a 'molecular framework'?

b) How do Turkish high school students explain the reaction of hydrogen and fluorine?

c) How do Turkish high school students understand chemical bonding?

d) What are the common features of Turkish high school students' ideas about chemical bonding?

The first question, *what proportion of Turkish high school students conceive of ionic bonding in terms of a 'molecular framework'*, refers to a published conceptual framework for explaining learners' ideas about ionic materials, based on a well-established set of ideas (deriving from earlier interview research). A published instrument offers a means of exploring the extent to which students think about ionic bonding in terms of discrete molecules, rather than in terms of electrostatic forces between ions (Taber, 1997). The 'Truth about Ionic Bonding' diagnostic instrument (Taber, 2002a), presents statements relating to both the target model presented in the curriculum, and statements linked to the common alternative conceptual framework. The English research suggests that students often give an inconsistent set of responses suggesting they are thinking with an amalgam of acceptable and alternative ideas. Testing out this finding in Turkey would be confirmatory research. Applying this instrument (suitably translated) in Turkey would allow a comparison of the response patterns (bearing in mind that the UK study did not use a representative random sample).

If Turkish findings were similar to those in the UK then this would suggest that whatever factors lead students to develop alternative ideas about ionic bonding (Taber, 2001a), are at work in both contexts – this might be significant if teaching of the topic in Turkey was very different to that in the UK. It might be even more significant if it was found that students in Turkey did not adopt the alternative ideas at all – or used them exclusively. Then differences between the two contexts may well be having a significant influence on student learning: something worth exploring further.

The second example question was *how do Turkish high school students explain the reaction of hydrogen and fluorine?* A simple diagnostic instrument used in the UK (Taber, 2002a) demonstrated that most college students thought the reaction occurred to allow the hydrogen and fluorine atoms to get full shells (Taber, 2002b): despite the probe giving students the equation for the reaction (showing the reactants as molecular). This instrument could also be used in confirmatory study in Turkey. However, unlike in the previous example, where students evaluated statements given by the researcher, this probe allows a free response. This means that it would be suitable for testing the hypothesis that Turkish students also apply an 'assumption of initial atomicity' (that reactions occur between substances comprised of discrete atoms) and see reactions as driven by the atoms' desires to fill their shells. However, if it transpired that many Turkish students had entirely different alternative conceptions for while reactions occurred, this could also be detected in the data.

The third question given as an example was *how do Turkish high school students understand chemical bonding?* This research question might be motivated by the studies in the UK and elsewhere demonstrating common alternative conceptions. However, this question does not assume that Turkish students will necessarily share ideas founds in other contexts. This study will start from no particular assumptions about what students may think, and so needs to follow the types of guidelines for exploratory interpretive studies outlined above - such as sequences of in-depth interviews, analysed through iterative stages of coding looking for the meanings students intend in their responses.

Finally, the fourth question, *what are the common features of Turkish high school students' ideas about chemical bonding?*, is one that can only be effectively asked as a further phase following form the previous type of study (Taber, 2000a). It makes no sense to look to see *how common* Turkish students' ideas are among wider populations, until in-depth work has identified the ways students in this particular cultural and educational context are thinking. Careful elicitation and characterisation of alternative conceptions is needed before candidates for common alternative conceptions can be conjectured.

It is implicit in setting out on any of this work that it is assumed that students in Turkey *may* not share the same set of ideas about science topics elsewhere, or else there would be no rationale for research into students' ideas in the topics that have already been studied elsewhere. (Instead teachers should be informed of the existing research studies from other contexts.) Given this premise, it should be clear here that research that directly draws upon findings from other contexts can proceed directly to a confirmatory stage *but* will at best find out the extent to which Turkish students share ways of thinking with those already reported. Such research when undertaken carefully and skilfully can provide genuine insights, but will probably only offer a partial account of how Turkish students are thinking.

A more informative approach starts with careful exploratory research so that later surveys are based on the range of conceptions that have been characterised in that educational context. As international research journals publish original and rigorous research from both the exploratory and confirmatory stage of the research process, a research programme that includes both types of studies would seem to have most potential to both inform teaching in Turkey and contribute to the international research programme.

CONCLUSION

In this paper I have discussed some of the types of research that can contribute to the research programme exploring student ideas and learning in science. I have suggested there are important differences between exploratory research, that investigates learners' thinking in depth, and the confirmatory approach used to test out the generality of findings from in-depth work or other contexts. Both types of research have limitations, so that moving our understanding forward depends upon the successive swings of 'the methodological pendulum', and carefully coordinating the two complementary types of enquiry.

Although there is still scope for useful studies looking at different groups of learners' thinking in different topics, there is now so much of this work in the literature that many such studies are only like to achieve publication in regionally based or practitioner journals unless they can offer major theoretical insights as well as new empirical accounts. That is, such studies need to do more than just report which alternative conceptions were found among particular groups of students.

It is suggested here that where researchers wish to explore learners' ideas in their own educational context, and wish to report their findings in the international research literature, they should consider the issues raised in this paper at the stage when they are planning and designing their research.

One potentially fruitful direction for research is to seek to offer sufficient details of educational and cultural context so that specific findings can be linked to contextual features that may illuminate some of the various factors that influence the origins and development of students' thinking. Such studies may have wider implications for the research programme, and for developing science pedagogy, than just informing teachers which particular conceptions may frequently be found among certain groups of learners.

REFERENCES

Abimbola, I. O. (1988). The problem of terminology in the study of student conceptions in science. *Science Education, 72*(2), 175-184.

Allen, D., Donham, R., & K, T. (2004). Approaches to biology teaching and learning: lesson study—building communities of learning among educators. *Cell Biology Education, 3*, 1–7.

Assessment of Performance Unit. (1989). *National assessment: The APU science approach*. London: HMSO.

Bell, B. (1995). Interviewing: a technique for assessing science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice* (pp. 347-364). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Biddle, B. J., & Anderson, D. S. (1986). Theory, methods, knowledge and research on teaching. in Wittrock, M.C., (Ed.), *Handbook of research on teaching* (3rd ed., pp. 230-252). New York: Macmillan.

Bodner, G. M., Klobuchar, M., & Geelan, D. (2001). The many forms of constructivism. *Journal of Chemical Education, 78*(Online Symposium: Piaget, Constructivism, and Beyond), 1107.

Brown, A. L. (1992). Design experiments: theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences, 2*(2), 141-178.

Cromer, A. (1997). *Connected knowledge: Science, philosophy and education*. Oxford: Oxford University Press.

diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction,* 10 (2&3), 105-225.

Driver, R., & Bell, B. (1986). Students' thinking and the learning of science: a constructivist view. *School Science Review*, 67(240), 443-456.

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

Driver, R., & Erickson, G. (1983). Theories-in-action: some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education,* 10, 37-60.

Duit, R. (2007). *Bibliograph-STCSE - Students' and teachers' conceptions and science education*. from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Duit, R., Roth, W.-M., Komorek, M., & Wilbers, J. (1998). Conceptual change cum discourse analysis to understand cognition in a unit on chaotic systems: towards an integrative perspective on learning in science. *International Journal of Science Education,* 20(9), 1059-1073.

Erickson, G. (2000). Research programmes and the student science learning literature. In R. Millar, J. Leach & J. Osborne (Eds.), *Improving Science Education: The contribution of research*. Buckingham: Open University Press.

Eybe, H., & Schmidt, H. J. (2001). Quality criteria and exemplary papers in chemistry education research. *International Journal of Science Education, 23*(2), 209-225.

Gardner, H. (1998). *Extraordinary minds*. London: Phoenix.

Geertz, C. (1973). Thick description: toward an interpretive theory of culture. In *the interpretation of cultures: Selected essays* (pp. 3-30). New York: Basic Books.

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*(4), 623-633.

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: changing perspectives in science education. *Studies in Science Education, 10*, 61-98.

Gilbert, J. K., Watts, D. M., & Osborne, R. J. (1985). Eliciting student views using an interview-about-instances technique. In L. H. T. West & A. L. Pines (Ed.), C*ognitive structure and conceptual change* (pp. 11-27). London: Academic Press.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. New York: Aldine de Gruyter.

Hennessy, S. (1993). Situated cognition and cognitive apprenticeship: implications for classroom learning. *Studies in Science Education, 22*, 1-41.

Herron, J. D. (1975). Piaget for chemists: explaining what 'good' students cannot understand. *Journal of Chemical Education, 52*, 146-150.

Keogh, B., & Stuart, N. (1999). Concept cartoons, teaching and learning in science: An evaluation. *International Journal of Science Education, 21*(4), 431-446.

Kind, V., & Taber, K. S. (2005). *Science: Teaching school subjects 11-19*. London: RoutledgeFalmer.

Kuhn, T. S. (1996). *The structure of scientific revolutions* (3rd ed.). Chicago: University of Chicago.

Kvale, S. (1996). *Interviews: An introduction to qualitative research interviewing*. Thousand Oaks, California: Sage Publications.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrove (Eds.), *Criticism and the Growth of Knowledge* (pp. 91-196). Cambridge: Cambridge University Press.

Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (Eds.). (1998). *Teaching science for understanding: A human constructivist view*. San Diego, California: Academic Press.

NRC. (2002). *Scientific research in education: national research council committee on scientific principles for educational research*. Washington DC: National Academies Press.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: a generative process. *Science Education, 67*(4), 489-508.

Petri, J., & Niedderer, H. (1998). A learning pathway in high-school level quantum atomic physics. *International Journal of Science Education, 20*(9), 1075-1088.

Phillips, D. C. (1987). *Philosophy, science and social enquiry: Contemporary methodological controversies in social science and related applied fields of research*. Oxford: Pergamon Press.

Pope, M. L., & Denicolo, P. (1986). Intuitive theories - a researcher's dilemma: some practical methodological implications. *British Educational Research Journal, 12*(2), 153-166.

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

Rosenthal, R., & Jacobson, L. (1970). Teacher's expectations. In L. Hudson (Ed.), *The ecology of human intelligence* (pp. 177-181). Harmondsworth: Penguin.

Rye, J. A., & Rubba, P. A. (1998). An exploration of the concept map as an interview tool to facilitate the externalization of students' understandings about global atmospheric change. *Journal of Research in Science Teaching, 35*, 521–546.

Solomon, J. (1993). Four frames for a field. In P. J. Black & A. M. Lucas (Eds.), *Children's informal ideas in science* (pp. 1-19). London: Routledge.

Taber, K. S. (1994a). *Can Kelly's triads be used to elicit aspects of chemistry students' conceptual frameworks?* Paper presented at the British Educational Research Association Annual Conference. from http://www.leeds.ac.uk/educol/documents/00001482.htm

Taber, K. S. (1994b). Student reaction on being introduced to concept mapping. *Physics Education, 29*(5), 276-281.

Taber, K. S. (1995). Development of student understanding: a case study of stability and lability in cognitive structure. *Research in Science & Technological Education, 13*(1), 87-97.

Taber, K. S. (1997). Student understanding of ionic bonding: molecular versus electrostatic thinking? *School Science Review, 78*(285), 85-95.

Taber, K. S. (1998a). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*(5), 597-608.

Taber, K. S. (1998b). The sharing-out of nuclear attraction: or I can't think about Physics in Chemistry. *International Journal of Science Education, 20*(8), 1001-1014.

Taber, K. S. (1999). Ideas about ionisation energy: A diagnostic instrument. *School Science Review, 81*(295), 97-104.

Taber, K. S. (2000a). Case studies and generalisability - grounded theory and research in science education. *International Journal of Science Education, 22*(5), 469-487.

Taber, K. S. (2000b). Chemistry lessons for universities?: A review of constructivist ideas. *University Chemistry Education, 4*(2), 26-35.

Taber, K. S. (2000c). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education, 22*(4), 399-417.

Taber, K. S. (2001a). Building the structural concepts of chemistry: some considerations from educational research. *Chemistry Education: Research and Practice in Europe, 2*(2), 123-158.

Taber, K. S. (2001b). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education, 23*(7), 731-753.

Taber, K. S. (2002a). *Chemical misconceptions - prevention, diagnosis and cure: Classroom resources* (Vol. 2). London: Royal Society of Chemistry.

Taber, K. S. (2002b). *Chemical misconceptions - prevention, diagnosis and cure: Theoretical background* (Vol. 1). London: Royal Society of Chemistry.

Taber, K. S. (2002c). Compounding quanta - probing the frontiers of student understanding of molecular orbitals. *Chemistry Education: Research and Practice in Europe,, 3*(2), 159-173.

Taber, K. S. (2002d). Conceptualizing quanta - illuminating the ground state of student understanding of atomic orbitals. *Chemistry Education: Research and Practice in Europe, 3*(2), 145-158.

Taber, K. S. (2002e). "Intense, but it's all worth it in the end": the colearner's experience of the research process. *British Educational Research Journal, 28*(3), 435-457.

Taber, K. S. (2003a). Lost without trace or not brought to mind? - A case study of remembering and forgetting of college science. *Chemistry Education: Research and Practice, 4*(3), 249-277.

Taber, K. S. (2003b). The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*(1), 43-84.

Taber, K. S. (2003c). Understanding ionisation energy: physical, chemical and alternative conceptions. *Chemistry Education: Research and Practice, 4*(2), 149-169.

Taber, K. S. (2005). Learning quanta: barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94-116.

Taber, K. S. (2006a). Beyond constructivism: the progressive research programme into learning science. *Studies in Science Education, 42*, 125-184.

Taber, K. S. (2006b). Constructivism's new clothes: the trivial, the contingent, and a progressive research programme into the learning of science. *Foundations of Chemistry, 8*(2), 189-219.

Taber, K. S. (2007). *Classroom-based research and evidence-based practice : a guide for teachers*. London: SAGE.

Taber, K. S. (2007/2008). Conceptual resources for learning science: Issues of transience and grain-size in cognition and cognitive structure [Electronic Version]. *International Journal of Science Education*, *iFirst Article (paper publication due 2008)*,

Taber, K. S. (Accepted for publication). College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education*.

Taber, K. S. (in press). Of Models, Mermaids and Methods: The Role of Analytical Pluralism in Understanding Student Learning in Science. In I. V. Eriksson (Ed.), *Science Education in the 21st Century*. Hauppauge, New York: Nova Science Publishers.

Taber, K. S., & Coll, R. K. (2002). Chemical Bonding. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust & J. H. Van Driel (Ed.), *Chemical Education: Research-based Practice* (pp. 213-234). Dordrecht: Kluwer Academic Publishers BV.

Taber, K. S., & Tan, K.-C. D. (2007). Exploring learners' conceptual resources: Singapore A level students' explanations in the topic of ionisation energy. *International Journal of Science and Mathematics Education, 5*, 375-392.

Taber, K. S., & Watts, M. (1996). The secret life of the chemical bond: students' anthropomorphic and animistic references to bonding. *International Journal of Science Education, 18*(5), 557-568.

Tan, K.-C. D., Goh, N.-K., Chia, L.-S., & Taber, K. S. (2005). D*evelopment of a two-tier multiple choice diagnostic instrument to determine a-level students' understanding of ionisation energy*. Singapore: National Institute of Education, Nanyang Technological University.

Tan, K.-C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., et al. (2007). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education, iFirst (paper publication due 2008?)*.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate student's misconceptions in science. *International Journal of Science Education, 10*(2), 159-169.

Watts, M. (1983). A study of schoolchildren's alternative frameworks of the concept of force. *European Journal of Science Education, 5*(2), 217-230.

Watts, M., & Gilbert, J. K. (1983). Enigmas in school science: students' conceptions for scientifically associated words. *Research in Science and Technological Education, 1*(2), 161-171.

Wightman, T., Green, P., & Scott, P. (1986). *The construction of meaning and conceptual change in classroom settings: case studies on the particulate nature of matter*. Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds.

Yager, R. E. (1995). Constructivism and the learning of science. In S. M. Glynn & R. Duit (Ed.), *Learning science in the schools: Research reforming practice* (pp. 35-58). Mahwah, New Jersey: Lawrence Erlbaum Associates.