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RESEARCH REPORT
Concept teaching and learning

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DEVELOPING STUDENTS' UNDERSTANDING OF CHEMICAL CHANGE: WHAT SHOULD WE BE TEACHING?

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ABSTRACT: Research over the last two decades has revealed that students' understanding of chemical change is very poor - even amongst those that have successfully passed public examinations. This paper argues that the underlying problem is located with the specification of the chemistry curriculum. Kinds of problems are identified. In particular, the curriculum does not directly address key ideas that students do not have and need to develop in order to understand 'standard' chemistry content. They have been assumed and in this sense they are 'missing' from our teaching. Such ideas are identified and the results of an intervention with undergraduate students on an Initial Teacher Training course (students who will teach in UK primary schools where the pupils are aged 5 -11) which did seek to address them are reported. These students have not studied chemistry or physics at tertiary level (16-18), are predominantly female and arrive with negative attitudes towards science. Data was collected by a questionnaire administered at the start and again towards the end of a first year physical science subject knowledge module. The findings do not lead to a rejection of the hypothesis and, indeed, give grounds for optimism. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 77-90]

KEY WORDS: *substance; chemical change; particle theory; curriculum specification; students' ideas; conceptual change*

INTRODUCTION

Secondary students' (11-16) understanding of chemical change has been the subject of considerable research in recent years (Andersson 1990; Driver, Squires, Rushworth, & Wood-Robinson 1994; Garnett, Garnett, & Hackling 1995; Stavridou & Solomonidou, 1998). Overwhelmingly, studies have revealed that students have a very poor understanding of all aspects of chemical change. Consistently, the students placed in anything approaching a scientifically acceptable category of response number less than 10%, frequently considerably less. Research on older students suggests that the difficulties persist post 16 (Abraham, Williamson, & Westbrook 1994; Barker 1995; Hesse & Anderson 1991; Taber 1998). What is to be made of this? Where are we going wrong? Is this the fault of the students (they are not up to it), the teachers (they cannot teach) or chemistry as a subject (it is of no interest students)? It has been argued elsewhere (Gott & Johnson in press) that the underlying problem is located with none of these, but lies with the *specification* of the chemistry curriculum. (The England and

Wales National Curriculum is assumed to be broadly representative of most chemistry curricula.) Quite simply, the curriculum does not specify the key ideas that students need to develop in order to understand chemical change (i.e. chemistry). The curriculum is not designed from the perspective of the learner. What we have is a curriculum where the specified content only makes sense if you *already* understand chemistry. This conclusion is based on the findings of a three year longitudinal study which explored the development of lower secondary students' understanding of the concept of a substance (Johnson 1995, 1996, 1998a, 1998b 1998c, 1999 a & 1999b) and an analysis of the literature.

Four 'kinds' of problems with the specification can be identified:

- Ideas that are 'missing' in the sense that they are not recognised as ideas that students will need to develop and will probably need time to come to terms with (we assume they are 'obvious' and they are not);
- 'Missing' ideas which highlight that we have not thought carefully enough about what we do teach (i.e. the curriculum itself is muddled);
- Wrong ideas;
- Unintentional promotion of misleading ideas that cause confusion.

An example of each of these is given below.

- Students do not have the idea of what science means by 'a substance'. They do not have a means of identifying a substance (other than by 'history') and certainly have no conception that 'gases' such as oxygen are just as much substances as, say, iron or water. Therefore, they cannot even begin to entertain the possibility of chemical change. Furthermore, the crucial role of the particle theory in developing the concept of a substance must be recognised (Johnson 1999a;1999b).
- The distinction between the *idea* of an element (which refers to atoms) and 'an element' as a type of *substance* is not made (Schmidt, 1998).
- Much early emphasis is given to reversibility as a criterion for distinguishing between chemical change and physical change. Chemical changes are said to be irreversible. Quite simply, this is wrong and, of course, the idea of a substance (which is necessary to recognising a change of substance) is ignored!
- A favourite activity of school science is to classify substances into 'solids', 'liquids' and 'gases'. This promotes the idea that there are 'three types of substance' and pupils then have great difficulty in understanding how a 'solid' such as copper can combine with a 'gas' such as oxygen (Johnson, 1999b).

We are not talking about peripheral problems here - these lie at the heart of understanding chemical change. The scientific concept of 'a substance' is the central issue, there is nothing obvious about what this is. And yet, our science teaching does not target this high order concept and all that it entails as something that needs to be developed. Instead, students are taught a great deal of 'information' (e.g. separation techniques with no emphasis on how we 'know' when we have a pure sample of a substance, activity series, acids, bases and salts, groups of the Periodic Table, etc.) which assumes that the idea of a substance is unproblematic. This paper will report on the progress of students on a subsequent course which attempted to identify and focus on the two categories of 'missing ideas' and avoid 'wrong' and 'misleading' ideas.

METHODOLOGY

The teaching was part of a physical science subject knowledge module for first year undergraduate students on an Initial Teacher Training (Primary) course (representing one sixth of a year's study). This module has been running now for four years, with around 85 students per year. These students have not studied chemistry (or physics) at tertiary level (16-18); a few have studied biology. The students are predominantly female and the vast majority start rarely with anything other than an antipathy towards science, having 'escaped' at 16 when no longer compulsory for them. A significant minority are mature students with almost no science background. Experience has shown that the students arrive with a very poor understanding of science - they exhibit all of the characteristic difficulties reported in the literature. The total teaching contact time for the module was 3.5 hours per week for 22 weeks. Of this, about half of the time was devoted to 'chemistry'. The students were taught in 3 groups, each with a different teacher. All students were given a module text (written by Johnson) and the teaching of all groups followed a 'workbook' which set out various activities requiring the students to apply the ideas introduced in the module text. In developing the concept of a substance and hence chemical change, the module sought to give emphasis to the following 'missing' ideas. The list is not exhaustive, but is intended to give a flavour of the approach:

- that we always have a sample of a substance;
- the distinction between properties of the substance and properties of the object(sample);
- how a sample of 'stuff' is identified as a substance;
- 'primary' and 'secondary' objects for the solid state (e.g. a pile of powder = 2^0 ; each grain = 1^0);
- that the question of purity refers to the sample not the idea of a substance - the term 'pure substance' is a nonsense;
- the identity of a substance is independent of state or mixing;
- the idea of a state only applies to pure samples of substances;
- the properties of a sample are determined by how the particles interact with each other as a collection - we need say nothing about the 'material' nature of the particles - individual particles do not have a state;
- particles have an ability to 'hold' on to each other;
- the distinction between bulk and individual motion of particles;

- substances are not conserved in a chemical change - they go out of and come into existence;
- the *idea* of an element (which refers to atoms) as being distinct from samples of *substances* that are called elements;
- decomposition as an idea that is particularly challenging;
- the problematic nature of identifying what is a chemical change and the many possibilities of even the simplest situation; e.g. heating a sample of a substance or adding something to water;
- the changing composition of a reaction mixture during the progress of a chemical reaction - there is not a sudden change from reactants to products;
- what a bond is in terms of a balance of forces;
- effective nuclear charge and not the number of outer electrons as the factor that determines the nature of bonding between atoms.

It is not being suggested that these are ‘missing’ from all curricula, but that typically they do not receive the direct attention they deserve.

Data were collected from the 1998/9 cohort of students through a questionnaire. This was administered in the first contact session of the module and then again (with the omission of unproductive questions) near the end of the module when all new material had been covered. The students were not given notice of the repeat and so they had not prepared for it (as indeed for the first time). The intention was to monitor their residual thinking rather than any performance temporarily boosted by revision. In fact, the second attempt marked the start of a two-week revision period leading up to their exams and their responses were used to inform this (the questionnaire played no part in the summative assessment of the students). The second version of the questionnaire is given in the Appendix. In addition, a small number of students were interviewed (n=8), but details of these will not be reported here.

RESULTS AND DISCUSSION

Categories and frequencies of responses for each of the questions are given in Tables 1 to 5 (the questions have been grouped together). A few words with respect to the validity of the percentages given in the Tables are needed. It must be noted that total number of students for the post questionnaire (n=52) is much lower than for the pre questionnaire (n=82). Unfortunately, the onset of ‘only’ a revision period and the imminence of exams in all of their modules resulted in a reduced number of students attending the session at the time. In addition, 13 scripts from one group were rejected on suspicion that parts of them had been completed at a later debriefing session (they were too good!). It is difficult to say whether the ‘loss’ of the 30 students has introduced any bias into the results. Another factor that must be considered is the difficulty of interpreting the students’ meanings for words (Johnson & Gott 1996). This is difficult enough in the interview situation where clarification can be sought, let alone a written response. Words such as ‘air, ‘oxygen’, ‘gas’, ‘react’ and ‘burn’ are particularly problematic, and, of course, these

TABLE 1. *Change of state involving the gas state.**

Bubbles in boiling water	***Pre***	***Post***
Water as a gas/vapour/steam	11	52
Air and water	4	6
Air / oxygen - trapped/ dissolved/ unspecified	27	12
Oxygen and /or hydrogen due to a change/break up of the water	48	27
Carbon dioxide - (origin unspecified)	6	2
No response	4	4

Loss of water from boiling water	***Pre***	***Post***
Turns to 'air'/gas/vapour/ steam	78	92
Water evaporates into air - general statement	10	0
Turns to oxygen and or hydrogen	10	6
Link made to the bubbles - stated or implied	12	19
Other	1	2
No response	0	0

Condensation on cold mirror	***Pre***	***Post***
Water as gas in air/moisture cooling down to form the liquid/attracted	27	75
Gas/air cooling down to form the liquid/water	16	15
Oxygen and or hydrogen recombining	2	4
Layer of some kind formed in fridge warming up	7	0
Vague statement temp differences - warm meeting cold	40	6
Other	6	0
No response	0	0

Use of particle ideas	***Pre***	***Post***
Particles/molecules moving apart to create space used to explain formation of bubbles	0	23
Loss of water from boiling beaker in terms of particles leaving	22	88
Condensation: specific mention of water particles being a part of the air	1	67
Balance between rate of leaving and rate of joining noted	0	23

* Pre: n=82. Post: n=52. Frequencies expressed are percentages.

TABLE 2. *'Number of substances'.**

Iron and rust	**Pre**	**Post**
2 - iron and rust are different substances	38	75
2 - iron and oxygen	1	6
1 - same substance but in different state/form	21	6
Other / question not answered as asked	33	10
No response	7	4

Solid and liquid wax	***Pre***	***Post***
1 - but in different states	66	92
2 - solid and liquid	10	2
2 - wax and water	5	0
Other / question not answered as asked	5	2
No response	13	4

Bread** ** and charcoal	***Pre***	***Post***
2 substances -decomposes/ something lost to leave carbon	6	25
2 - something adds / reaction with something to form the carbon	17	13
2 - no reason	30	46
1- but in different form	13	8
1 -in same state	4	0
Other / question not answered as asked	13	4
No response	15	4

The two charcoals	***Pre***	***Post***
1 - both decomposed to leave carbon	4	19
1 - stated as both carbon/charcoal	9	41
1 - same thing happened	12	2
2 - started as different substances	21	13
Other / question not answered as asked	28	12
No response	24	12

Water	***Pre***	***Post***
1 substance	33	84
2 - is hydrogen and oxygen	32	12
Other / question not answered as asked	23	4
No response	11	0

* Pre: n=82. Post: n=52. Frequencies expressed are percentages.
** It is recognised that bread is a mixture of substances. This did not seem to trouble the students in the pre-module questionnaire. This issue was addressed in the module. In the post-module questionnaire a number of students did draw attention to this. Overall, the question was answered in the spirit in which is was asked.

TABLE 3. *Reaction of copper with oxygen to give copper oxide. **

Meaning of 'reacts'	***Pre***	***Post***
Combination of copper with oxygen	52	87
'Effect' of oxygen on copper	29	8
Other / question not answered as asked	16	4
No response	1	2
Change in mass of copper to copper oxide	***Pre***	***Post***
More - extra mass due to the added oxygen	23	63
Same - oxygen has no mass	5	2
Same - is same thing/ amount copper /just changed form	23	8
Less - oxygen is light	2	0
Less - something lost	13	17
Less - no reason / other	13	0
Other / question not answered as asked	7	6
No response	10	6
Number of substances	***Pre***	***Post***
3 - copper , oxygen and copper oxide	28	85
2 - copper and oxygen	32	12
2 - copper and copper oxide	6	0
Other / question not answered as asked	18	0
No response	12	4

* Pre: n=82. Post: n=52. Frequencies expressed are percentages.

featured very prominently in the responses. Here, the challenge was greatest in the pre-module questionnaire, since the students' use of such terms was more liberal. Given these issues the precise percentages must be viewed with caution. Nevertheless, a number of general points can be made.

Firstly, the results of the pre-module questionnaire confirm that the students had arrived with a poor grasp of the scientific ideas. In particular, they did not have a robust idea of what was meant by 'a substance' that incorporated its key facets. Consequently, there was nothing to

TABLE 4. *Overall categories for the candle. **

Candle	*Pre*	*Post*
An interaction where wax and oxygen change into carbon dioxide and water.	2	21
An interaction between wax and oxygen. New substances are formed (which uses up the oxygen and wax) but some problems with the details (usually with the water).	4	35
Appreciates that both wax and oxygen are involved but no link to new substances formed.	2	40
Wax is not directly involved. Oxygen becomes carbon dioxide - stated but not explained. The wick is a main focus.	15	0
Wax is not directly involved. Can go no further than oxygen is 'needed'/ 'reacts'/ 'burnt up'. Carbon dioxide may be mentioned but this is not linked to the oxygen. Some may say that water is produced by a separate reaction between oxygen and hydrogen in the air. The wick is a main focus.	72	0
No response/ other	2	4

* Pre: n=82. Post: n=52. Frequencies expressed are percentages.

structure their thinking - the pattern was of isolated 'successes' at some questions. Overall, the teaching seems to have had a positive effect - there is a clear move towards the scientific now all relatively high. Using a crude measure of 1 point per scientifically acceptable category, the average score changed from 4.5 to 9.4 out of a maximum of 13. However, when the students' performance across the questions is considered, a more cautionary outcome emerges. Table 5 shows a modest 40% answering all of the 'number of substances' correctly and, as more of the areas are included, a progressive reduction to 4% correct for all of the questions. The demands that even the small the range of events used make upon the idea of a substance must not be underestimated. To the learner, there is much to keep in mind and much to ignore (in terms of noise) to see the 'simplicity' of the underlying picture.

The results tables highlight ideas that seem to present a particular challenge. The idea that the bubbles in boiling water are water itself as a body of gas - so 'simple' as it might seem to us - was not readily accepted by half of the students. Many still wanted the 'gas' to be 'a gas' in the sense of something that they 'knew' to be 'a gas'; e.g. air, oxygen or hydrogen (we see the influence of thinking in terms of 'types of substance' here). They were far more comfortable with the idea of evaporation, where water left at its surface to join an existing body of gas - the air.

Table 1 shows only 23% of the students using the idea of particles moving apart to create their own space to explain the formation of the bubbles. Whereas 88% talked in terms of water particles leaving from the surface (they had no need for oxygen and hydrogen). There seems to be something about the formation of bubbles that troubled many of the students. Decomposition as a type of chemical change also proved to be a greater challenge than composition. For the 'two charcoals', a relatively low 60% said they were the same and only 19% specifically argued

TABLE 5. *Overall categories.**

Definition of substance	***Pre***	***Post***
Acceptable (properties / particles/ as elements and compounds)	21	73
Linked to elements only	17	6
Interpreted in terms of the three states	15	4
Other / question not answered as asked	33	13
No response	13	2

Overall category	***Pre***	***Post***
'Copper oxide' correct - excluding mass	21	77
'Copper oxide' all correct	11	56
All 'number of substances' correct - excluding decomposition	9	69
All 'number of substances' correct **	4	40
'Number of substances' excluding decomposition and all 'copper oxide' correct	2	48
All 'number of substances' and 'copper oxide' correct	2	27
All number of substances, copper oxide, evaporation and condensation correct	1	21
All number of substances, copper oxide, evaporation and condensation and boiling bubbles correct	1	14
All correct (number of substances, copper oxide, evaporation and condensation, boiling bubbles and candle)	0	4
Average score out of maximum of 13 (on a crude measure of 1 point per correct category)	4.5	9.4

* Pre: n=82. Post: n=52. Frequencies expressed are percentages.
** The first three categories in 'bread and charcoal' and first two in 'the two charcoals' are counted as correct.

in terms of decomposition. This, of course, has implications for introductory definitions of 'elements' as substances that cannot be decomposed. The change in mass for copper to copper oxide was another problematic area. For those that did acknowledge that copper and oxygen were combining, a sizeable minority still insisted that something/ some of the copper was lost (but not in the sense of a decomposition). Perhaps this was an attempt to account for the change from 'a lump' to a powder? A few students still had difficulty with the idea of 'a gas' such as oxygen having a mass. Finally, Table 4 shows that the students found the candle to be the most challenging of all the events. All of these points that emerge from the data replicate the findings of the three-year study (Johnson 1995) - even in their relative magnitudes. Either they are a factor of teaching material designed by myself or they arise from fundamental interactions between learners and the ideas themselves. If the latter, then our teaching should take note of these. A limitation of the questionnaire data is that it does not probe the relationship between structure and bonding and specific properties. The module does address this in some detail and this is a matter to be pursued in future research.

CONCLUSIONS AND IMPLICATIONS FOR INSTRUCTION

The hypothesis informing this work is that students' difficulties with chemistry are symptomatic of a curriculum where important ideas are 'missing'. Yes, the sorts of ideas listed earlier are implied by the standard content of the chemistry curriculum. However, the point is that they are not explicitly stated as ideas that need to be the target of our teaching. It cannot be assumed that students will 'pick up' these ideas merely by exposure to content which derives its meaning from them and at the same time appreciate those ideas that are wrong and disregard those that are misleading. Although the students still have some way to go, the results of this study are taken to be encouraging; they do not speak of a 'resistance to change' as is so often stated. The findings do not reject the hypothesis and suggest that there is merit in continuing with this approach. Once the ideas are 'in the open' what the results do emphasise is the time that might be necessary for some students to fully come to terms with them. (One factor for these students is the possible handicap of having to overturn previous learning in school.) Perhaps the most pleasing aspect of the students' response to the module is in their changed attitude towards science. The students have come to accept and value science as being something within their grasp - they can appreciate that there is 'something there' which does make sense - and their antipathy has been turned around. Module evaluations have always been very good and they recognise that the approach is very different from 'school science'. Indeed, many students have become positively enthusiastic and even opt for more science! If nothing else, this change within the affective dimension suggests that the students' needs as learners are being met in a way they have not experienced before. Of course, it is one thing for older students to make progress, this does not necessarily translate to younger secondary students. However, if it is accepted that the secondary chemistry curriculum is wanting in its specification then it follows that we do not know what our school students might be able to achieve. It could be argued that they are hardly being given a 'fair chance' to show what they can do. Certainly, we must not write them off as if they were the problem, nor the ability of teachers to teach and nor the subject itself. What is being proposed here is a deficit model of the curriculum, not students, teachers or the subject - the specification of the curriculum needs to be improved. It will require a significant change to present practice and more systematic and thorough research to get the specification right. The 'missing' ideas listed above should be seen as a start towards this end. These kinds of ideas are fundamental to developing an understanding of chemical change and, therefore, need attention no matter what the context of the chemistry content - whether traditional or STS. With a curriculum which is better matched to the needs of our students as learners there is the prospect of much improved achievement and interest in chemistry.

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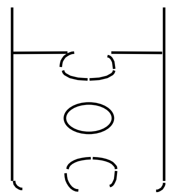
APPENDIX: POST-MODULE QUESTIONNAIRE

Apart from a few omissions and one addition, this questionnaire is the same as the pre-course questionnaire. Please have another go at the questions. Afterwards, there will be a chance to compare these latest answers to your previous ones! Again, please express your ideas as clearly as you can. Use simple language and try to avoid using scientific jargon for its own sake. You are encouraged to draw diagrams and/or to annotate any existing diagrams to help convey your meanings. If you run out of space for any answer, please use the back side of the paper.

1. When a beaker of water is boiling, big bubbles form at the bottom and rise to the top. These bubbles are clear inside - 'see through'.

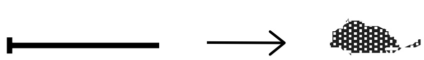


   a) What is inside the bubbles; i.e. what are the bubbles made of? Explain how this can be.
   ……………………………………………………………………………………………

   b) If a beaker of water is kept boiling for a long time, it can be seen that the level of water in the beaker goes down. Explain why this happens. Be as specific as you can about how the water is 'lost' from the beaker.
   ……………………………………………………………………………………………

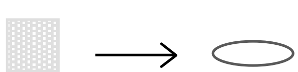
2. A small mirror is left in a fridge for an hour. It is then taken out, wiped dry with a paper towel, and then left to stand in a room. After a few minutes, the surface of the mirror 'mists up'.
   a) What is the 'mist' on the surface of the mirror?
   ……………………………………………………………………………………………
   b) Explain how this mist forms on the mirror
   ……………………………………………………………………………………………

3. a) If an iron nail is left outside for a very long time, a quantity of red/brown powder will be found in its place.



   Imagine you have an iron nail and a pile of this red/brown powder on the table in front of you. How many substances would there be on the table? Explain your answer.

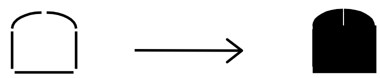
   b) If a lump of white wax is warmed, a pool of clear liquid is found in its place.



   Imagine you have a lump of wax and a pool of this clear liquid on the table in front of you. How many substances would there be on the table? Explain your answer.

....

c) If a slice of bread is held down in a toaster for 10 minutes a crispy black slice emerges. This is black through and through.



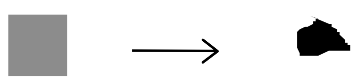
Imagine you have a slice of bread and one of these black slices on the table in front of you. How many substances would there be on the table? Explain your answer.
....

The same thing will happen with a slice of *wood* held down in a toaster. Imagine you had a black slice that had started as wood and a black slice that had started as bread in front of you on the table. How many substances would there be on the table? Explain your answer.
....

d) Imagine you have a drop of water in front of you on the table. How many substances would there be on the table? Explain your answer.
....

e) This question has been about substances and their identity. Try to give a definition of what is meant by 'a substance', which includes how they can be identified.
....

4. A stamp-sized piece of copper foil is heated in the air over a blue bunsen flame. After a short while the foil is taken out of the flame and it can be seen to have turned black. In fact, a black powder can be scraped from the surface to leave a thinner piece of copper. If the heating and scraping process is repeated a number of times, we eventually end up with a pile of black powder and no foil. The explanation of this is that the copper is said to react with oxygen (from the air) to form copper oxide.

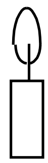


a) What do you think is meant by 'react with oxygen'?
....

b) Imagine that we start with a piece of copper foil with a mass of exactly 1g. It is then all reacted with oxygen to produce copper oxide (as described in (a)). All of the copper oxide is then placed on a very sensitive balance. How would the mass of the copper oxide compare to the 1g mass of copper that we started with? Explain your answer.
....

c) Imagine you have a piece of copper, a jar of oxygen and a pile of copper oxide in front of you on the table. Ignoring the glass of the jar itself, how many substances would there be on the table? Explain your answer.
....

5. The diagram shows a lighted candle.



a) What is happening to the wax? Say as much as you can
....

b) What is the flame?
....

c) Is anything coming out of the flame? If so, what? Explain how.
....

d) Sometimes we say the candle is 'burning'. What is it that is actually burning?
....

A jar is now put over the candle. Two key observations are that the candle goes out and that the inside of the jar mists up.

e) People say that the candle goes out because it 'runs out of oxygen', or the 'oxygen is used up'. Explain how it is that a candle needs oxygen to stay alight. Exactly what does the oxygen do?
....

f) The mist on the inside of the jar is water. How is it that this mist appears on the glass?
....

REFERENCES

Abraham, M.R., Williamson, V.M., & Westbrook, S.L. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching*, *31*, 147-165.

Andersson, B. (1990). Pupils' conceptions of matter and its transformations (age 12-16). *Studies in Science Education*, *18*, 53-85.;

Barker, V. (1995). *Conceptual change in 16-18 year old chemistry students: Results of a longitudinal study.* Paper presented at the Science Education Research in Europe conference, Leeds, UK.;

Driver, R., Squires,A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science - research into children's ideas* (London: Routledge)

Garnett, P., Garnett, P., & Hackling, M. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education*, *25*, 69-95.

Gott, R. & Johnson, P (in press). Science in schools: time to pause for thought? *School Science Review*.

Hesse, J. & Anderson, C.W. (1991). Students' conceptions of chemical change. Journal of Research in Science Teaching, *29*, 227-299.;

Johnson, P.M. (1995). *The development of children's concept of a substance: A three year longitudinal study. PhD thesis*, University of Durham, School of Education.

Johnson, P. M. (1996) What is a substance? *Education in Chemistry*, *33*, 41-42.

Johnson, P. M. (1998a) Progression in children's understanding of a 'basic' particle theory: A longitudinal study. *International Journal of Science Education*, *20*, 393-412.

Johnson, P. M. (1998b) Children's understanding of changes of state involving the gas state. Part 1: Boiling water and the particle theory. *International Journal of Science Education*, *20*, 567-583

Johnson, P. M. (1998c) Children's understanding of changes of state involving the gas state. Part 2: Evaporation and condensation below boiling point. *International Journal of Science Education*, *20*, 695-709.

Johnson, P. M. (1999a) Children's understanding of substances, Part 1: Recognising chemical change. *Paper submitted for publication*.

Johnson, P. M. (1999b) Children's understanding of substances, Part 2: Explaining chemical change. *Paper submitted for publication*.

Johnson, P. M. & Gott, R. (1996) Constructivism and evidence from children's ideas. *Science Education*, *80*, 561-577.

Schmidt, H. (1998) Does the Periodic table refer to chemical elements? *School Science Review, 80*(290), 71-74.

Stavridou, H. & Solomonidou, C. (1998). Conceptual reorganization and the construction of the chemical reaction concept during secondary education. *International Journal of Science Education*, *20*, 205-221.

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