Students' explanations of chemical phenomena: macro and micro differences.

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Abstract

This study investigated patterns of students' science thinking across four different science phenomena, focusing on changes with age and science education. British secondary school students in three age-groups were offered sentences appearing on a computer screen that gave different explanations for four common changes in materials: ice melting, sugar dissolving in water, a candle burning and an iron nail rusting. The students were asked whether the sentences 'made sense' to them. The sentences, composed of fixed terms, were designed to embody good science explanations, common misconceptions, and basic descriptive and causal categories relating to the physical world. They were generated from a systemic network of explanation types. Results enabled new distinctions to be made between students' ideas at substance, molecular and atomic level according to their length of time in science education. Implications regarding the age at which students are introduced to atomic theory are considered.

Introduction

In many domains of science we now have a detailed picture of how children's understandings of events in the natural world differ from the science understanding of the same events (Driver *et al*. 1994). This picture has been achieved by asking students, in one way or another, to explain some physical event. However, most of the studies from which this picture has been built have restricted themselves to considering student understanding of a single phenomenon, or at most of a series of related phenomena presented one at a time, such as those of melting, boiling and evaporation (Osborne & Cosgrove 1983). Moreover researchers have usually not explicitly asked students at what level they are applying an explanation that they give, and unless a student spontaneously mentions particles, it is implicitly assumed that what they say about substances also applies to their understanding of what is happening at particle level (Meheut *et al.,* 1985; Stavridou & Solomonidou 1989; Stavy, 1990; BouJaoude 1991; Ebenezer & Erikson 1996; Lynch 1996;Watson *et al.,* 1997). One of the aims of the present study was to explore whether students' explanations of changes in materials apply across different phenomena, in other words, whether we are looking at explanation types rather than simply at an explanation of an individual event. The results reported here consider the types of explanation that students find acceptable across phenomena at the substance, molecular and atomic level.

In the research, a computer combined fixed items from a grammar of explanation types (Reynolds & Brosnan, submitted) to produce on the screen sentences that were designed to embody good science explanations, common alternative conceptions drawn from the literature on children’s ideas in science, and sentences that fell into neither category. They were designed to elicit students' understandings of four different phenomena - burning, rusting, dissolving and melting - that had been separately investigated in previous research (Andersson & Renstrom 1982a; Osborne & Cosgrove 1983; BouJaoude 1991).

One important reason for explicit investigation of the level at which students believe certain changes to be possible is the view, commonly found in the science education literature, that many children believe that when a substance changes, the particles that make it up change in the same way. (Ben-Zvi *et al.,*1988; Andersson 1990). For example, when explaining the melting of ice, many say that its molecules also melt. (Dow *et al* 1978). Similarly, when explaining the disappearance of a substance, many appear to believe that the particles that made it up have disappeared. (Prieto *et al* 1989) Evidence of such beliefs was also found in the present study. However, unless questions about level are explicitly asked, conclusions of unwarrented breadth may be drawn about students' beliefs.

In the computer sentences our design made explicit provision for students to comment not only on the properties of substances but separately on those of atoms and molecules of the substances: Would it make sense to say these changed size, shape or colour? Can they get weaker or stronger? Can they be made or disappear? By examining students' preference for terms appropriate to substance, molecular and atomic levels of explanation, this study enabled us to obtain an indication of students' theoretical level in chemistry, irrespective of the accuracy of their knowledge about specific chemistry phenomena. The results enabled new insights to be gained into the significance of macro/micro distinctions made by students.

Method

Sample

From three age groups, a total of 82 participants were selected for spread of science ability by collaborating science teachers in three co-educational state secondary schools in north London and from two independent London single-sex schools. There were twenty-seven 11 and 12-year-olds (Year 7 students), twenty-nine 13, 14 and 15-year-olds (Year 9 and 10 students) and twenty-six 16 and 17-year-olds (Year 12 students). Most of the latter were studying at least one science, though not necessarily chemistry, at 'A' (advanced) level.

Apparatus

A portable computer operated by the participant displayed sentences (Fig1) explaining changes in each of four everyday phenomena, ice melting, sugar dissolving in water, a candle burning and an iron nail rusting. The computer sentences sometimes mentioned the substances involved in a change, sometimes their atoms and sometimes their molecules. Each sentence offered a description of the change and some also offered a possible cause for the change. Some of the sentences constituted acceptable science explanations, some were intended to embody misconceptions drawn from the literature on children's ideas in science, and some fell into neither category. Except for the words 'atoms' and 'molecules', the terms used in the sentences were deliberately non-technical. The participants indicated by clicking on a button whether the sentences '*made sense', 'did not make sense'* or *'might make sense'* to them. The computer saved the sentences each participant was offered, and a record of their choice of button in responding to each. This process, with further student comments and discussion with the researcher, was audiotaped for each student.

Box 1: Examples of sentences produced by the computer

1. WHEN AN IRON NAIL RUSTS, THE WATER COMBINES WITH SOMETHING.
2. WHEN AN IRON NAIL RUSTS, ATOMS OF IRON ARE MADE.
3. WHEN A CANDLE BURNS, MOLECULES OF OXYGEN REARRANGE BECAUSE THEY REACT WITH THE WAX.
4. WHEN A CANDLE BURNS, ATOMS OF OXYGEN COME INTO VIEW.
5. WHEN ICE MELTS, THE ICE CHANGES FORM BECAUSE IT DOES THAT WHEN IT IS WARM.
6. WHEN ICE MELTS, MOLECULES OF WATER DISAPPEAR.
7. WHEN SUGAR DISSOLVES IN WATER, THE SUGAR DISAPPEARS.
8. WHEN SUGAR DISSOLVES IN WATER, THE MOLECULES OF SUGAR CHANGE INTO SOMETHING NEW BECAUSE THEY REACT WITH THE WATER.

Procedure

Participants were told that the researchers had devised a teaching programme which used computer-produced sentences to explain to children four everyday changes in materials. Since it was a computer which produced the sentences , it was likely that some of them would not make sense to students. We wanted participants' help in knowing which sentences to discard, and so we were asking them which made sense to them personally, and which did not. The terms *makes sense, does not make sense* or *might make sense* were used, rather than 'correct' or 'incorrect', because student knowledge or ignorance of the science account of each of the four phenomena was not the focus of our interest. Rather, we wanted to know if there were *types* of explanation that were acceptable to students across different phenomena, and if so at which levels (substance, molecular or atomic). The participants were individually offered, in a single session, an average of 40 sentences for comment, averaging 10 per phenomenon (burning, rusting, melting, dissolving). They were asked the reasons for their choices and were also asked to give their own explanation for the phenomena. The procedure was piloted with 10 science graduates in initial teacher training. Some changes in the terms used in the sentences were made as a result.

Data analysis

The session transcripts were analysed and the responses classified, using definitions (Table 1) produced by us for this study. Single responses or comments were not taken in isolation as an indicator of a student's theoretical level in science. Rather, a broad, overall relationship was proposed between a student's responses to the computer sentences with their additional comments, taken as a whole, and a theoretical level as defined in Table 1.

Table I: Levels at which change terms used in the computer sentences could in principle be applied to substances, molecules and atoms

Terms used to describe the change	Level at which the use of these terms to describe the change is in principle possible
Melts, dissolves, burns, is made, disappears, changes form, changes shape, changes size, changes colour, gets weaker/stronger, rearranges	Substance
Are made, disappear, change form, change shape, change size, get weaker/stronger, rearrange	Molecules
Rearrange	Atoms

Table I shows the most important terms used in the computer sentences to describe the changes involved in melting, rusting, dissolving and burning and the level at which we considered that in principle such terms could legitimately be used, irrespective of phenomenon, given the nature of substances, molecules and atoms.

Again using transcripts and responses to computer sentences, students were classified at one of three levels (Table II) All transcripts were read and assigned by the researcher. In the classification of students at ‘macro’, ‘micro’ or ‘within-micro’ level, 12 scripts from each age-group were assessed independently by a microbiologist with a good knowledge of chemistry. There was agreement on classification of 100% of the Year 7 transcripts 92% of the Year 9/10 transcripts and 92% of those of Year 12.

Table II: Criteria for judging a student to be at 'macro', 'micro' or 'within-micro' level

'macro'	A computer sentence mentioning molecules or atoms is accepted where the change it describes cannot apply in science terms except at the substance level.
	A student asks what molecules are (or atoms if no distinction seems to be made) or says that they do not know what they are
	- frequently says 'don't know' in response to sentences mentioning atoms or molecules but not when responding to 'macro' sentences.
	- ignores 'atom' or 'molecule' in sentences by using 'it' in responses, or by mentioning the substance only.
'micro'	A sentence describing a change and mentioning molecules or atoms is rejected on the grounds that the change cannot happen at that level.
	There is evidence of understanding that some change descriptions cannot apply to molecules and atoms.
'within micro'	There is frequent explicit reference to inter- or intra-molecular features of a change

Preferred explanatory level

Participant responses were analysed (see Table III) to classify participants' 'preferred explanatory level'. ('Preferred explanatory level' is explained in the Results section). Here we used the word 'correct' to mean 'not impossible in science terms' at a particular level, irrespective of factual correctness for a particular phenomenon. 'Not impossible in science terms' indicated that the type of change described could without contradiction be attributed to substances, molecules and atoms respectively and as such. (Table I gives examples) We use the word 'spontaneously' to mean 'offered in the computer sentence and also specifically mentioned by the student in the response' or 'not offered in the computer sentence, but mentioned in the response'. There is no spontaneous aspect to a response when an offered sentence merely receives a response of 'makes sense', 'might make sense' or 'does not make sense' with no further comment.

Table III: Protocol used for classifying student responses to obtain their 'preferred explanatory level'

1. Macro sentence, macro response[a] - Category used whether the student judges the computer sentence to be sensible or not, and where there are (a) no further student comments or (b) further comments at macro level only. Correctness irrelevant. (c) when 'don't know' or 'might make sense' is accompanied by comment at macro level.
2. Macro sentence, micro response - A macro computer sentence usually received initially a macro response, but category 2 is used (a) when spontaneous comments refer to molecules or atoms or (b) molecules or atoms are mentioned in response to probes (in both cases irrespective of the correctness of what may be ascribed to these particles) (c) when a 'don't know' or 'might make sense' response is accompanied by comment referring to molecules or atoms.

3. Macro sentence, within micro response - Category used when, in response to a computer macro sentence, (a) spontaneous references to structure, bonding, changes in movement, energy or spatial arrangement (with respect to each other) are ascribed to molecules or atoms (b) any change description except one of rearrangement is spontaneously rejected for atoms. (c) when a 'don't know' or 'might make sense' response is accompanied by comments as in 3a) above.
4. Micro sentence, macro response - Category used when (a) a computer sentence uses 'molecules' or 'atoms' (plural terms) but 'it' is used in the response (this being taken to indicate a reference to the substance) (b) following a computer sentence referring to molecules or atoms, only the substance is referred to in spontaneous comments or in response to probes (c) a sentence referring to molecules or atoms, and describing a change impossible at micro level, is accepted without comment.
5. Micro sentence, micro response - Category used when a computer sentence referring either to molecules *or* atoms receives a response that could be correct at molecular level, with or without a comment.[b] (Correctness of judgment at *atomic* level irrelevant.)
6. Unclassifiable Any response not classifiable by the above criteria.

[a] The number of responses in this category was extremely small and is not reported.

[b] It is recognized that this is likely to overestimate preference at the 'micro' level, since where a student does not comment we cannot assess any meanings they may attach to the terms 'molecule' and 'atom'. Few failed to comment, however.

Results and discussion

The 82 participants were presented with computer-generated sentences and their responses analysed. It was found that the same type of explanation of a phenomenon may differ in its acceptability to students at substance, at molecular and at atomic level. It is argued that acceptability of types of explanation at different levels may be used to characterise a student's overall theoretical level in chemistry, and that the terms that students use in spontaneous comments provide additional evidence of their theoretical level.

The students were classified as being at one of three levels. To the first (‘macro’) level were assigned those who made no distinction between substances, molecules or atoms. (Maskill *et al* 1997). Students identified as being at the second (‘micro’) level did differentiate between substance and particles, but they did not distinguish within the micro level. Those judged to be at the ‘within-micro’ level provided evidence of a clear understanding of the differences between atoms, molecules and substances.

Table IV: Numbers of students classified at 'macro', 'micro' and 'within-micro' level by age-group. The proportion within an age-group is in brackets

	'Macro'	Beginning micro	'Micro'	'Within micro'	Not classified	*n*
11-12 years	19 (70%)	6 (22%)	0	0	2 (7%)	27
13-15 years	13 (45%)	6 (21%)	3 (10%)	1 (3%)	6 (21%)	29
17 years	2 (8%)	0	7 (27%)	16 (62%)	1 (%)	26

Table IV shows numbers of students classified according to the criteria in Table II. It shows a clear difference in theoretical level between the three age groups in the sample. The 11-year-old students are exclusively at macro level on the criteria used, though a proportion of these suggested the beginnings of micro understanding. There is a particularly high level among the 17-year-olds of explanations that fully distinguish between substances, molecules and atoms. This did not surprise us, since most of these students were science specialists, but it may not be typical of students of this age (Stavridou & Solomonidou 1998). Within the 13-15-year-old group, the combined total of students who could not be classified and those whose transcripts suggested the beginnings of micro understanding was almost equal to the number of students clearly at 'macro' level. The transcripts of students from this age-group, together with several from 11-year-olds, sometimes suggested individuals who were struggling to express difficult and only partially understood new ideas (Prieto *et al* 1993).

When we assessed the students' level of understanding, their responses were classified according to an 'in principle' criterion (Table I) rather than according to the factual correctness of their responses. This was because we were interested in explanation *types* that were applied at different levels rather than in particular explanations for particular phenomena. For example, it was common for a student to say they were unsure whether a reaction took place in dissolving. If on the whole they thought it did, they might accept 'changes form,' as a description of what happened to the molecules. In this case the student would be credited with 'micro' understanding since molecules can change form. What we would want to know on the basis of other responses from this student was whether they thought atoms could change form.

Students who were classified as being at 'macro' level ignored the terms 'molecules' and 'atoms' in sentences and accepted and used identical terms to describe changes irrespective of whether molecules, atoms or the substance was mentioned. These students, we surmised, either understood particles to be small versions of substances, or simply attached no meaning to the words 'molecules' or 'atoms' that could be separated from the meaning they attached to the word for the substance. Examples are given in Fig 2.

Fig 2: Examples of responses from students who made no distinction between levels

Computer: WHEN A CANDLE BURNS, THE MOLECULES OF CANDLE CHANGE FORM

Student: *Makes sense. It melts and changes shape.*
Computer: WHEN SUGAR DISSOLVES IN WATER, THE MOLECULES OF SUGAR DISAPPEAR **Student**: *Yes, it does dissolve in hot water.*
Computer: WHEN ICE MELTS, THE ATOMS OF ICE COMBINE. **Student**: *I only know that it melts*

A small subset of this group showed signs of possible beginnings of micro understanding. Recognizing such beginnings and considering what they might consist of is, of course, of great importance. The authors noted many instances in which certain features of what students said indicated a move away from reliance on simple observation towards a degree of speculation about the nature of micro entities, informed to a degree, no doubt, by recollections of what they had been taught. The potential importance of speculation in learning science is argued elsewhere (Reynolds & Brosnan, 2000). Examples of utterances which may suggest the beginnings of micro understanding (but do not use the term 'particle') are given in Fig 3.

Fig 3: Examples of responses from students that may suggest the beginnings of micro understanding

Computer: WHEN AN IRON NAIL RUSTS, THE ATOMS OF IRON ARE STILL THERE BUT CANNOT BE SEEN **Student:** *There might be some parts which rust really properly and then it all goes but then there might be tiny little bits left that…still have the power of iron in them.*

Student's own account of sugar dissolving in water: *Sugar…like…you put it in and the water - the water molecules are, like, heavier, and they push it down…and it seems to have disappeared. They're, like, really small and the water molecules are stronger and they, like, push it around.*
Computer: WHEN AN IRON NAIL RUSTS, THE ATOMS OF IRON CHANGE SHAPE **Student:** *They might weaken or become broken…they begin to corrode…and the bonds are going to get weaker* **[of what?]** *Of the element - the iron.*

In the first quotation in Fig 3, despite the understanding of iron atoms as 'tiny little bits', there is a suggestion in the use of the phrase' the power of iron' (rather than simply 'iron') of some defining feature of iron which endures through the changes it undergoes. In the second, there seems to be a synthesis of the observable behaviour of sugar grains with molecular rearrangement. In the third, the observable effects on the iron ('weaken', 'become broken', 'corrode') are transferred to the notions of bonds.

The students identified as being at the 'micro' level typically had about two years' chemistry teaching and their responses were therefore likely to have expressed science learning outcomes. 'Micro' level students were usually 13-15 years old, although examples of older and younger students who fell into this category were also found. These students accepted sentences that described changes at the atomic level which are only possible at molecular level, and in spontaneous comments they used the terms 'atom' and 'molecule' interchangeably. Unlike students at the third level, described later, they did not comment when 'impossible atoms', such as atoms of water, were mentioned in the computer sentences. Examples are given in Fig 4.

Fig 4: Examples of responses that did not differentiate within the micro level

Computer: WHEN A CANDLE BURNS, ATOMS OF CANDLE ARE MADE. **Student:** *Well, the candle atoms are…already there. Same with the ice, when the ice melts. They spread apart.*
Computer: WHEN ICE MELTS, `THE ATOMS OF ICE GET WEAKER. **Student:** *Makes sense. The molecules and the atoms* [get weaker].
Computer: WHEN ICE MELTS, THE ATOMS OF ICE ARE STILL THERE BUT CANNOT BE SEEN.

Student: *They're still there, but in a different form. They're all there, but they've just changed a little bit.*

In the first quotation in Fig 4, there is no comment that candle wax can exist only as molecules, and the comparison with ice melting introduces a change which is likely to have been taught explicitly as a molecular phenomenon. The difference between molecules and atoms is ignored. In the second, molecules are explicitly introduced by the student alongside atoms, but no differences between them as to the suitability of the change description '*get weaker'* are noted. In the third, the change descriptions the student applies to atoms are impossible by our criteria, (Table I) though conceivably applicable to molecules.

In our 'micro' classification we are open to the criticism that a student may simply not have noticed whether 'molecules' or 'atoms' was used in a computer sentence and so their response may not reflect their understanding of these particles. This may have happened in some cases. However, students classified as being at our third ('within-micro') level did regularly distinguish and comment on the use of 'molecules' and 'atoms' in the sentences, and this alertness to the terms used constituted in itself an indicator of theoretical level. Fig 5 gives examples.

Fig 5: Examples of responses that distinguished between molecular and atomic levels

Computer: WHEN ICE MELTS, THE ATOMS OF ICE MELT. **Student:** *There aren't atoms of ice, there's molecules of water. And the bonds between the molecules of water sort of melt.*
Computer: WHEN A CANDLE BURNS, THE ATOMS OF OXYGEN DISAPPEAR. **Student:** *Doesn't make sense. They bond with other atoms to create something new.*
Computer: WHEN AN IRON NAIL RUSTS, THE ATOMS OF WATER CHANGE SHAPE.

Student *Atoms don't change shape. Actually…atoms include electrons. I'm just trying to work it out because if it's ionic it's going to have lost electrons anyway. I'm going to say it might make sense, but it needs a lot of clarification.*

The terms the students used in spontaneous comments – their 'preferred explanatory level' - provided additional evidence of their theoretical level. We placed students in one of four categories of 'preferred explanatory level' as follows:

1. Those who tended to give macro explanations whether the computer sentence mentioned substances, molecules or atoms;
2. Those who responded to or commented on an explanation at the same level as that offered by the computer sentence;
3. Those who, whatever the level offered by the sentence, tended to give explanations at molecular or atomic level;
4. Those who, whatever the level offered by the sentence, tended to refer to structure, bonding, changes in movement, energy or spatial arrangement in their response.

Table V shows the proportions of responses in each category by age-group.

Table V: 'Preferred explanatory level': proportion of responses at given levels, by level of prompt offered in computer sentences

	macro prompts (N)	micro prompts (N)	macro prompts resulting in micro responses (%)	micro prompts resulting in micro responses (%)	micro prompts resulting in within-micro responses (%)
11-12 yrs.	363	386	4.2	66.0	2.2
13-15 yrs.	468	429	4.7	72.2	1.4
16-17 yrs.	409	457	17.8	58.8	28.2

Outcomes specifically of school learning were not the focus of this study, and were not the subject of questions to students. In commenting on the explanations they were offered, or in offering their own, however, students rarely referred to what they had learned in school.

Discussion and implications for science education

This research investigated types of explanations favoured by students for four everyday changes in materials, and results reported here focus on the level at which students considered certain change descriptions to be possible. It was found that there were differences by age in the degree to which the same type of explanation would be accepted at substance, at molecular and at atomic level.

Between the ages of 11 and 16 years, there was no clear-cut advance among our students in understanding of the different types of change that are possible at substance and at micro level; neither was there much sign before the age of 17 years of their feeling at home with the language of the micro world. It was also notable that students rarely referred to what they had learned in school as they commented on the explanations they were offered, despite the fact that they were told that the computer software was being trialled for use as a teaching aid. The dramatic increase both in understanding and in use of appropriate language at 17 and 18 years is likely to have been due to the fact that while the science studies of the younger students had not yet systematically introduced them to atomic theory, those in the older group were science specialists. There is some evidence (Gabel 1993; Maskill *et al.,*, 1997) that children are capable of understanding particle theory earlier than they are usually given credit for, and that this facilitates other aspects of their science understanding.

This should perhaps be given consideration in the planning and review of science curricula.

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