Research in Science & Technological Education

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/crst20

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Published online: 28 May 2008.

Research in Science & Technological Education
Vol. 26, No. 2, July 2008, 165–183

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This paper reports the findings of a study exploring the use of a software package to help pupils understand particulate explanations for melting and evaporation below boiling point. Two matched classes in a primary school in Greece (ages 11–12, n = 16 and 19) were involved in a short intervention of six one hour lessons. Covering the same phenomena and particle ideas, one class was taught using the software simulations, the other was not. Data were collected pre and post intervention through individual interviews (n= 2 × 12). In an approach which included the ideas of an 'ability to hold' and a distribution of energy, both groups made progress, but there were indications that the software had helped and more so for evaporation. However, in other cases, pupils could not escape from their initial views and created synthetic explanations with both macroscopic and microscopic characteristics.

Keywords: particle theory; melting; evaporation; educational software

Introduction

Changes of state have featured prominently in science education research over recent decades with studies covering all points along the primary–secondary continuum (for example Andersson, 1990; Bar and Travis, 1991; Costu and Ayas, 2005; Lee et al., 1993; Osborne and Cosgrove, 1983; Russell, Harlen and Watt, 1989; Stavy, 1990). Although there appears to be cross-age progress in understanding such phenomena, problems still remain, especially in changes involving the gas state (Bar and Galili, 1994; Johnson, 1998b, c; Paik et al., 2004; Tytler, 2000). Some suggest progress would be enhanced if particle ideas were embodied earlier in the educational process (Johnson, 1998a, b, c; Leisten, 1995; Skamp, 1999; Tsai, 1999). This runs counter to the wider consensus which regards the particle model as too difficult, especially for younger pupils (Fensham, 1994; Harrison and Treagust, 2002). The National Curriculum for England covers changes of state in primary school but declares that particle ideas 'need not be taught'. Similarly, in Greece they do not feature in such contexts at this level. We assume the perceived conceptual demand on pupils is the primary reason for the omission. In Piagetian terms, particle theory involves late formal thinking which is far beyond the vast majority of primary pupils (Shayer and Adey, 1981). Although, primary teachers' understanding in this area is not strong (see for example Kokkotas, Vlachos, and Koulaidis, 1998; Papageorgiou and Sakka, 2000), short-term practicalities aside, it would be strange to deny pupils access to ideas they were capable of because their teachers were deemed incapable.

In our view, there is the possibility that pupils' reported difficulties with the particle model could be more a function of an inadequate conceptual induction than excessive intrinsic demand (Johnson, 1998a). The model is usually introduced in the context of explaining the characteristics

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ISSN 0263-5143 print/ISSN 1470-1138 online

DOI: 10.1080/02635140802037336
http://www.informaworld.com

of 'solids', 'liquids' and 'gases' without regard to the distinction between a substance and a mixture of substances. Furthermore, the entry level model fails to account for different melting and boiling points. This can give rise the notion of 'solids', 'liquids' and 'gases' as three distinct types of substance (separate species) where changes of state are seen as isolated and somewhat confusing exceptions (Johnson, 1996). Nor does the model reconcile boiling and evaporation into the air below boiling point (Johnson, 1998c). This results in a confused blurring of the important distinction between a change of state (which takes place at a specific temperature) and a mixing phenomenon (which can take place over a range of temperatures). The common misconception ascribing macroscopic character to particles is a logical extension of three types of substance: often, apparently confirmed by a language featuring 'solid particles', 'liquid particles' and 'gas particles'. Alternatively, talk of the particles 'in a 'solid'/'liquid'/'gas' and certain textbook diagrams may mislead other pupils to a restricted model of extraneous particles embedded in the continuous substance. Essentially, the general principle that *a substance* can be in any of the three states is not taught directly. Certainly, we believe this line should be explored before current policy is accepted unconditionally. Accordingly, we have carried out small-scale exploratory experiments on introducing particle explanations to 9–11 year olds (Johnson and Papageorgiou, 2007; Papageorgiou and Johnson, 2005). Results have been promising and support Metz's (1995) critique of developmental assumptions regarded as constraints on elementary school science curricula. A good proportion showed profit from their engagement with the model and some developed a high level of understanding. Overall, teaching changes of state on a purely macroscopic basis seemed to be a limiting prescription.

Encouraged by the response to our conceptual approach, a next research objective is optimising its teaching by appropriate means. A computer-based multimedia platform would appear to have much to offer (Mayer, 2001). We have developed software with simulations concerning the states of a substance and changes during melting and evaporation below boiling point. The study reported here explored the impact of these simulations on primary pupils' understanding.

Multimedia learning and instruction

From a cognitive science perspective, Mayer and Moreno (2003, 43) define multimedia learning 'as learning from words and pictures' and multimedia instruction as 'presenting words and pictures that are intended to foster learning'. They identify three underpinning assumptions about how the human mind works (Mayer and Moreno, 2003, 44):

Dual channel	Humans possess separate information processing channels for verbal and visual material.
Limited capacity	There is only a limited amount of processing capacity in the verbal and visual channels.
Active processing	Learning requires substantial cognitive processing in the verbal and visual channels.

The first gives rise to the conviction that a multimedia approach offers advantages: two channels complementing each other ought to be better than one. The second warns against cognitive overload and the third embodies a constructivist view of learning. Fundamentally, meaningful learning is an active process (carried out in short-term memory) where the learner uses existing knowledge (in long-term memory) to make sense of, and derive new understandings from, sensory information (resulting in changes in long-term memory).

For the visual channel, a computer offers the facility of animation which can be used to construct a simulation: 'a computerized version of a model, which is run over time to study the implications of the defined interactions' (Baser, 2006, 368). Simulations offer opportunities for learners to explore particular events, to initiate processes, and to probe conditions (Tao and Gunstone, 1999; Zacharia, 2005; Zacharia and Anderson, 2003). Learners can face scientific conceptions for a phenomenon, compare them with their own conceptions, change them or reinforce them and thus develop their understanding. Appropriately designed simulations can isolate specific situations from the complexity of reality. Although distance from a real situation may create problems (Baser, 2006), simplification can focus on important aspects. With specially constructed tasks a learner can formulate predictions, make observations and devise explanations (Tao and Gunstone, 1999).

Any teaching resource is deployed within an overarching pedagogy. The use of computers is often associated with discovery methods of teaching. A number of researchers support this approach and suggest that if a simulation is well designed it can lead to knowledge construction. (De Jong and Van Joolingen, 1998; Veermans, Van Joolingen, and De Jong, 2006). Others emphasise the use of computers in the context of collaboration between learners (Tao and Gunstone, 1999; English and Yasdani, 1999; Hakkarainen and Sintonen, 2002; Tao, 2004). Discovery is always present and the whole process becomes a 'collaborative discovery learning' process (Gijlers and De Jong, 2005). However, there is no necessary association between kind of resource and instructional approach. Kirschner, Sweller, and Clark (2006) maintain that there is little evidence to suggest unguided or minimally guided instruction is effective, particularly for novices with little prior knowledge. They argue that the absence of guidance places too great a load on working memory (short-term memory). Thus, the use of a simulation requires careful planning in terms of supporting guidance and associated teaching strategies (Hsu and Thomas, 2002; Windschitl and Andre, 1998). However, fundamentally, the effectiveness of a simulation must surely rest on the appropriateness of the curriculum content and design (Hsu and Thomas, 2002; Zacharia, 2005; Zacharia and Anderson, 2003). As noted earlier, this study is set in the context of a new conceptual approach to the particle model. The software was but part of a unit of work and was accompanied with supporting guidance: it was not a stand alone 'discovery' programme.

Multimedia and chemistry

Chemistry content can operate at three levels: the macroscopic, the sub-microscopic and the symbolic (Johnstone, 1991) – an obvious candidate for a multimedia approach, one might think. For example, using a computer-based visualising tool which allowed students to build 3D molecular models and view multiple representations simultaneously, Wu, Krajcik, and Soloway (2001) report improved understanding of representations. Others have investigated the use of particle simulations in chemistry teaching (for example Ardac and Akaygun, 2004, 2005; Chiu, 2006; Greenbowe, 1994; Kozma and Russell, 1997; Russell et al., 1997; Sanger, 2000; Shrank and Kozma, 2002; Stieff and Wilensky, 2003; Velazquez-Marco et al., 2004; Willamson and Abraham, 1995). Overall, findings suggest a beneficial effect and there is evidence for the superiority of dynamic images over static images (Ardac and Akaygun, 2005). However, these studies have focussed on older students (from high school to college), have addressed particles in terms of atom structures, and have included the symbolic level. In short, they have dealt with complex material.

Snir, Smith, and Raz (2003) have used software with grade 5 and 6 pupils which introduced particle ideas in the context of mixing alcohol and water, thermal expansion and the reaction between copper and sulphur. The approach was through the consideration of competing models, without simulations as such. With the immediate inclusion of expansion and chemical change, it differs from our proposed line of attack. Overall, little is known about the value of simulations when introducing a 'basic' particle model (one that talks of particles of a substance rather than atom arrangements) and especially to young children.

A curriculum for teaching particle ideas – melting and evaporation

Ausubel, Novak, and Hanesian (1978) argue that progressive differentiation of a more general idea (subsumptive learning) is less demanding than integrative reconciliation (the recombination of existing elements). They recommend 'curricula should be planned to introduce the major concepts or propositions early in the course as a cognitive anchorage for subsequent learning' (Ausubel, Novak, and Hanesian, 1978, 352). In the context of this study, the concept of 'a substance' is the anchoring idea for the particle theory (as opposed to 'solids', 'liquids' and 'gases'). Figure 1 gives an outline of the teaching scheme.

First, the distinction between properties that only depend on the material and those that also depend on the object (amount of material and design) is made. Melting behaviour is then used to define 'a substance'. At this point, the particle model is brought in to explain why a substance can exist in both the solid and liquid states and why different substances have different melting points. The tenets of the model used are:

- A sample of a substance is a collection of particles.
- The particles of one substance are all the same and have a particular shape.

1. Properties and the material/object distinction

Some properties depend on the material only.

Some properties depend on the material, the amount (dimensions of an object) and the shape/structure of an object.

2. Definition of a substance

Melting behaviour can be used to distinguish between a pure sample of a substance and a mixture of substances.
Melting point and its use to identify a substance.
The characteristics of the liquid and solid states.

3. The particle model

Particle ideas can explain melting.
A sample of a substance was presented as a collection of particles with empty space between. Key points were:

- The particles have an ability to 'hold on' to each other;
- They are always moving in some way (energy of movement); and
- The particles of a particular substance remain the same in a change of state.

4. A sample of a substance could be in one of three states

A sample of a substance can be in the gas state.
Why different substances can be in different states at room temperature.

5. Mixing and unmixing

Evaporation below boiling point into the air.
Evaporation of a sample of water at room temperature.
Air as a mixture of substances in the gas state.
Factors affecting the rate of evaporation (surface area, temperature, breeze and substance).

Figure 1. Outline of the teaching scheme.

- The particles have an ability to hold on to each other – this is different for different substances.
- The particles are always moving in some way – they have energy of movement.
- Heating gives particles more energy to move.

The inclusion of an 'ability to hold', as a characteristic of a particular substance (rather than forces linked to generic states), was a distinctive feature of the particle model employed. Thus, change of state is explained as a change in the 'balance' between the energy of the particles (which changes with temperature) and the ability of the particles to hold on to each other (which does not change). Different strengths of hold account for different melting and boiling points (hence different room temperature states). This model can then be used to explain the gas state and hence, establish the general principle that a substance can exist in any of the three states (thermal decomposition of some substances will be a differentiation for later). By linking the model to pure samples of substances, the complex behaviour of mixtures is avoided. For evaporation below boiling point (a mixing phenomenon), the model was extended with the idea of a distribution of energy amongst particles. At a particular temperature there would be 'high', 'medium' and 'low' energy particles, with more 'high' energy particles at higher temperatures. In a liquid sample at room temperature there would be some high energy particles which could overcome the 'hold' and escape (if they happened to be at the surface). Simultaneous bombardment by high energy air particles ejects others. We believe this step-by-step approach, with a clear coherent message has a much lower intrinsic cognitive load (Danili and Reid, 2004; Sweller, 1994) than the more standard introduction of particle ideas.

Within the context of the above scheme of work, simulations of particle behaviour were developed. The software targets the particulate nature of substances in the three states and the events of melting and evaporation below boiling point in particular. Paik et al. (2004) suggest that changes involving an invisible state are more challenging than those between two visible states (for example, melting), but the route from a visible state towards an invisible state (for example, evaporation) is easier than the reverse (for example, condensation). Therefore, melting was chosen in order to investigate a relatively accessible event and evaporation below boiling point as a more difficult (but, hopefully, not too difficult) case. We preferred evaporation below boiling point, over boiling, to raise ideas of energy distribution amongst particles.

The software

After some introductory information, the master screen has activated photographs of water in the solid, liquid and gas states. Selecting a photograph brings a new screen showing the macroscopic image of the state together with a 'magnification' button. Repeated clicking of this button gives the sense of a progressive magnification and then a screen with the message: 'If we could magnify this a very large number of times, then…'. One further click gives a particle animation showing movements and relative distances. In addition, a thermometer indicates a temperature and two bars show comparative values for the 'energy' of the particles and their 'ability to hold'. Figure 2 is a snapshot for the liquid state.

Melting and evaporation below boiling point

The master screen also gives access to specific sections on melting and evaporation below boiling point. For melting, a piece of ice is presented at a temperature of −15°C. The user can change the temperature and when it reaches 0°C the lump is seen to melt through a sequence of still images (Figure 3). Simultaneously, a 'magnification' button appears on the screen. Repeated clicking leads

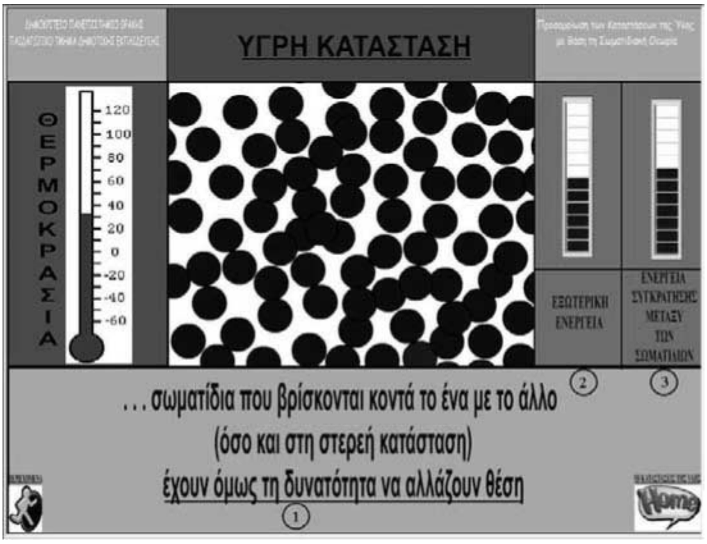

Figure 2. This simulation for the liquid state shows particles moving around randomly. A thermometer on the left shows a typical temperature for this state. Text (1) helps the user to make observations and give explanations for some significant points. On the right two bars indicate comparative values of the particle 'energy' (2) and the 'ability to hold' (3).

to a particle simulation of the event (Figure 4). A collection of vibrating particles in fixed places gradually changes to random translational movement, with no noticeable increase in spacing.

Similarly, a simulation of evaporation (Figure 5) can be reached.

In the design of instructional software, Mayer and Moreno (2003) caution against cognitive overload. As seen in Figures 2–5, screen displays had five sections and this holds the danger of

Figure 3. Initially, the macroscopic image of a piece of ice at –15°C is presented. When the user changes the temperature by clicking the activated word 1, the temperature becomes 0°C and the piece of ice starts to melt (as above). Underneath, text (2) describes the main points. On the right, a bar indicates the 'energy' (3).

Figure 4. A simulation of melting. At this moment, particles at region 1 are moving about randomly whereas particles at region 2 are vibrating in fixed positions. In time, all particles move around randomly. On the right, two bars indicate comparative values for 'energy' (3) and the 'ability to hold' (4).

a 'split-attention effect'. In mitigation, pupils used the software in groups and guiding narration was provided by the class teacher at times. We would argue that there was no extraneous material adding to the demand on processing channels. Furthermore, the step-by-step approach amounted to pretraining and was largely under the control of the users (a beneficial segmentation

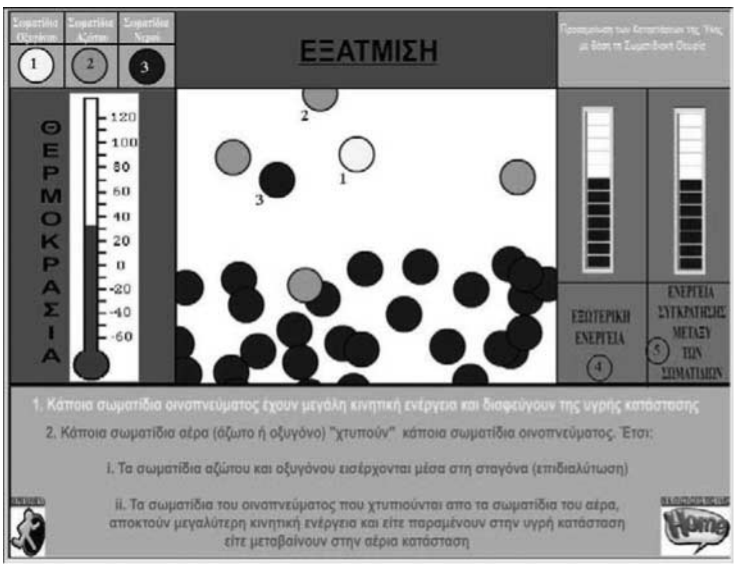

Figure 5. A simulation of evaporation below boiling point with oxygen (1), nitrogen (2) and water (3) particles. At this moment, a particle of nitrogen is bombarding the water particles and one high energy water particle has just escaped.

effect). Nevertheless, the proof of the pudding is in the eating. The study reported here explored the impact of this software on pupils' understanding.

Methodology

Two 6th grade classes (ages 11–12, n = 16 and 19) of a town primary school in northeast Greece took part in the study. The town is medium sized and has a socioeconomic level of around average for the country. The school was a normal public school where places are gained according to vicinity. As such, we estimate its range of pupils typifies the schools serving the town. Both classes were mixed ability (with similar average performance across subjects) and had followed the National Science Curriculum for Greece (Greek Pedagogical Institute, 1999) using the same textbooks prior to our intervention. To this extent, they were as well matched as any parallel groupings found in schools.

Two series of six one-hour lessons covering the same main points of the scheme of work (Figure 1) were designed for the two classes, respectively. Alongside simple demonstrations, one series (taught to class S) incorporated software simulations and the other (taught to class T) relied on more 'traditional' static representations (though broaching particle ideas at all with such pupils was far from traditional). Pupils used the software in groups of twos and threes. Under the direction of the teacher, they were asked to make *predictions* about the movement, spacing and interactions between particles for a state or phenomenon. On playing the appropriate simulation, the pupils could then make *observations* on the particle behaviour. Instructional guidance on screen (see Figures 2–5) as well as input from the teacher helped to direct attention (Ardac and Akaygun, 2004; Zacharia, 2005). Group discussions ensued followed by a teacher-led plenary session where questions invited *explanations* (for example, why a low energy particle cannot escape). The whole process has many similarities with the Predict-Observe-Explain (POE) tasks described by Tao and Gunstone (1999) in their work on 'force and motion microworld' using computer supported instruction. The simulations formed part of the learning process (Zacharia and Anderson, 2003) and only one or two tasks were used in a one hour lesson. Other activities (for both groups) included demonstrations such as melting a piece of wax or the evaporation of a drop of alcohol. Both classes were taught by the third author.

A sample of pupils was interviewed individually in the week before and a month after the intervention by the author who had taught the lessons. This consisted of six boys and six girls from each class. On the basis of their science assessments in the previous year, two boys and two girls were selected from high, intermediate and low bands of performance for each class. The same interview was used on all occasions. This was of the 'clinical type', using objects and events as stimuli for questioning (Posner and Gertzog, 1982). Figure 6 presents an outline of the interview tasks and questioning. Part one explored the pupils' conceptions of the particle model itself. The second part addressed their application of particle ideas to the two events in particular focus. Post-interviews lasted up to an hour whereas pre-interviews were usually much shorter due to pupils' limited ideas about particles. The delay in the post-interview was designed to avoid any temporarily remembered forms of words; that is their responses would reflect changes in conceptual understanding (meaningful learning) rather than rote recall.

Results and discussion

Part 1 of the interview (Figure 6) explored pupils' particle models for different states. These are reported first, followed by their explanations for melting and then evaporation.

Part 1
a) Particle pictures of solid, liquid and gas states
A single grain of sugar is shown. The pupil is asked to imagine magnifying the grain a huge number of times and to draw what would be seen. He or she is asked to label their diagram (the particles and what is between them) and to explain it.
The same is repeated for a drop of water and a sample of oxygen contained inside a jar.

b) Describing the nature of particles
The pupil is asked to describe:

- how (s)he imagines one particle from each of sugar, water and oxygen
- if (s)he could recognise different states in a single particle of water

NB. In the pre-interview there was no prompting for particle ideas. If no mention, there was no part (b). In the post-interview, prompting was planned. However, all but one pupil referred to particles spontaneously.

Part 2
c) Explaining melting
A lump of wax is heated. The pupil is asked to describe and explain what happens. What kind of material is the liquid that is produced? Why does wax melt? The pupil is encouraged to draw diagrams to help with his or her explanation.

d) Explaining evaporation (below b.p.)
A drop of ethyl alcohol is put on the table and left for a few minutes until it has completely evaporated. The pupil is asked to explain what happens to the alcohol and encouraged to draw diagrams.

e) Factors affecting evaporation (below b.p.)
The pupil is asked to predict and later to explain what happens when:

- A lamp (heating) is put over one of two drops of ethyl alcohol left (separately) on the table.
- A drop of water and a drop of ethyl alcohol are left (separately) on the table.

Figure 6. An outline of the interview questioning.

Pupils particle models

Figure 7 defines pupil particle model response categories (after Johnson, 1998a) and Table 1 gives their frequencies for the two classes pre and post instruction. Figure 8 tracks the changes between categories.

Both classes had encountered particle ideas the year before, briefly, in accordance with the Greek National Curriculum (Greek Pedagogical Institute, 1999). However, this was directed at the idea of electrons and an electric current and not states and changes of state. Unsurprisingly, Table 1 shows a poor grasp of the more basic particle ideas pre-intervention. For two thirds, the questioning effectively meant nothing (X and XA) and only one pupil from each class saw the particles as being the substance regardless of state (B). Post-intervention, almost three quarters had moved to B or above. A quarter showed a good understanding of the collective view (C) and were able to use the relation between ‘ability to hold’ and ‘energy’ to explain the different states

Table 1. Frequencies of pupils' particle models.

	Class T		Class S	
Type	Pre	Post	Pre	Post
X	5	–	4	–
XA	3	1	4	–
A	1	1	1	1
AB	2	1	2	3
B	1	3	1	2
BC	–	4	–	2
C-	–	–	–	1
C	–	2	–	3

of different substances at room temperature (for one this was more implicit than explicit). With the categories placed as they are, Figure 8 shows all of the pupils making 'positive' moves. This supports the suggestion that the order represents a progression in the development of pupils' understanding (Johnson, 1998a). Many made large gains.

Explaining melting

After seeing wax melt, pupils were asked to describe and explain the event, using particle diagrams if possible (section c, Figure 6). Table 2 presents categories and frequencies of their

Model **X**: Continuous substance – particle ideas have no meaning.

Model **A**: Particles **in** the continuous substance. In a particle diagram, the substance is said to be between the particles.

Model **B**: Particles **are** the substance, but they have macroscopic character. In a particle diagram, the particles represent the substance – they are literally small bits of it.

Model **C**: Particles **are** the substance and properties of state are explained by their collective behaviour.

Intermediate models also arise:

Model XA: A for the solid state, but X for the liquid and gas states

Model AB: B for the solid state, but A for the liquid and gas state, or B for the solid and liquid states but A for gas state.

Model BC: C for a substance in different states (particles do not change) but B for different substances in different room temperature states.

Figure 7. Particle model response categories.

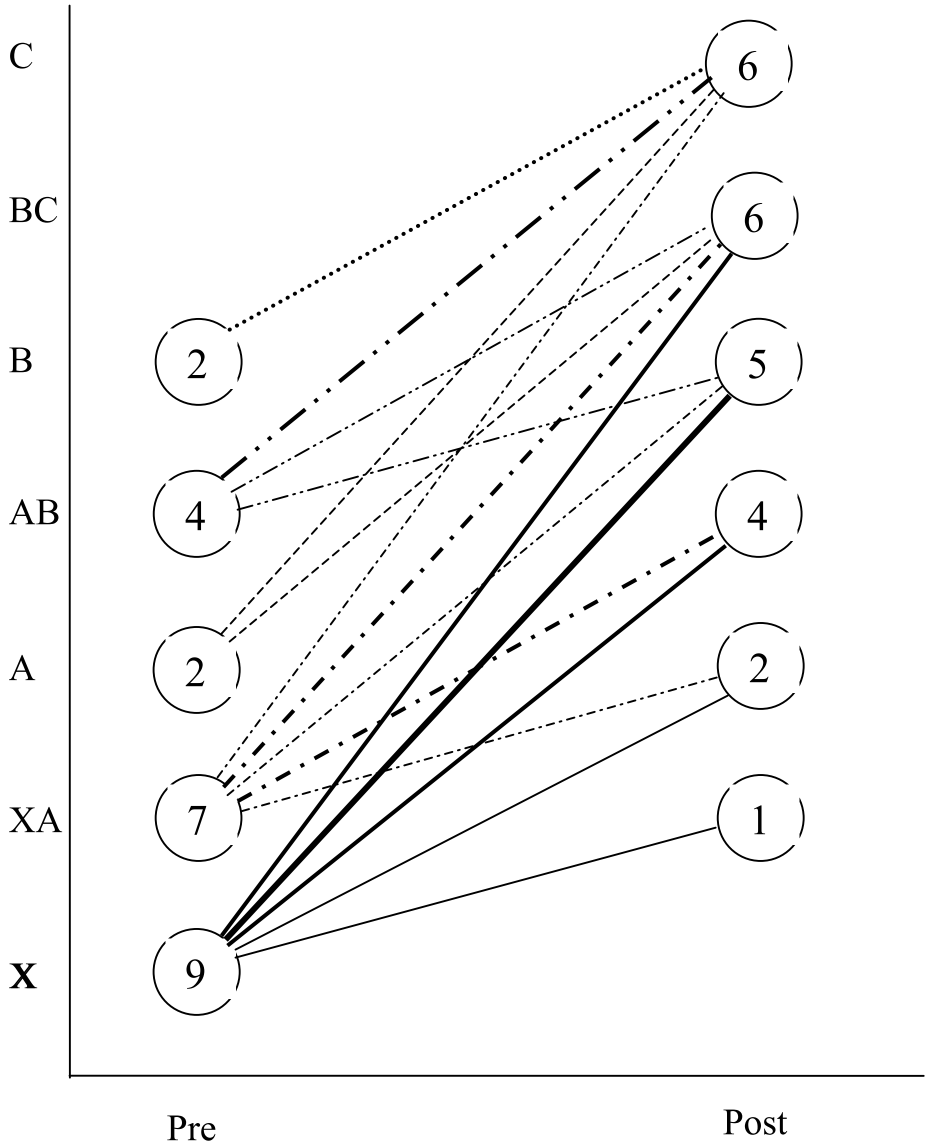

Figure 8. The changes in pupils' particle models. (Different line thicknesses represent 1, 2 or 3 pupils).

responses, and Figure 9 tracks the changes between categories. Pre-intervention, only four interviewees in each class made some mention of particles in their explanations (category 2). These included all in B and AB and one from each class in XA (Table 1). None of these showed signs of thinking beyond the macroscopic characteristics of the particles and for the XA pupils the identity of the particles which were 'destroyed' was unclear. The majority either gave macroscopic descriptions (solid changing to liquid due to heating) or offered nothing when asked to explain (category 3). Some of these pupils were not sure about the identity of the liquid (four in class S and three in class T).

Post-intervention, all participants recognised the liquid as still being wax and there was a movement towards particulate thinking. Those in the first category used the relative movements

Table 2. Categories and frequencies of pupils' explanations of melting.

Category	Pre		Post	
	Class T	Class S	Class T	Class S
1 Explanations based on the relevant movements of particles.	–	–	4	6
2 Explanations attributing 'macroscopic' characteristics to particles (particles melt or they are destroyed due to heating).	4	4	7	5
3 Explanations (mainly) at the macroscopic level (due to the heating) or no explanation.	8(3*)	8 (2*)	1*	1*

Note: * They referred to particles, but they couldn't use them in their explanations.

of particles to explain the change in state. Of these, all in C (Table 1) referred explicitly to the relation between 'energy' and 'ability to hold'. The remainders in category 1 were BC pupils (two of the four in class T and all three in class S) where this was only implied. Below category 1, all did at least talk of particles, even though the best still transferred macroscopic characteristics, for example, 'as the temperature arise, the particle of wax melt and droplets of wax are formed'. However, since Figure 9 shows most in category 2 pre-intervention moving to category 1, some thinking about particles might represent progress towards the science view. These pupils may be better placed to profit from a repeated intervention.

Explaining evaporation below boiling point

Results given in Table 3 and Figure 10 show the changes between categories. Pre-intervention, only two of the eight pupils who had made some reference to particles for melting did so here

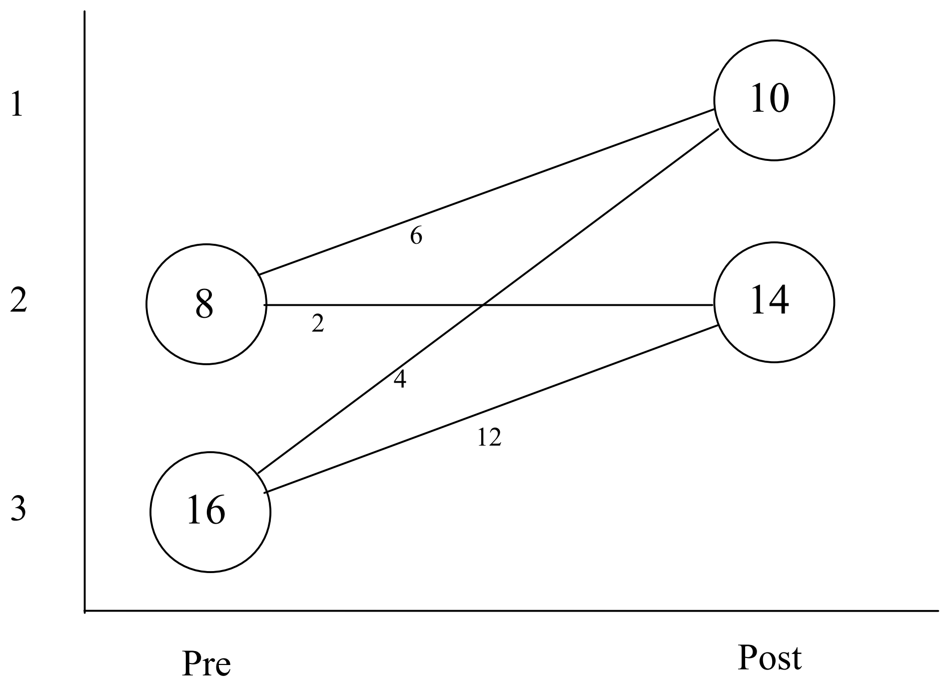

Figure 9. Changes in pupils' explanations of melting.

Table 3. Categories and frequencies of pupils' explanations of evaporation.

Category	Pre		Post	
	Class T	Class S	Class T	Class S
1 Explanations based on the relevant movements of ethyl alcohol and air particles. Escape of high energy alcohol particles and ejection by bombarding air particles.	–	–	2	5
2 Explanations only in terms of ejection by bombarding air particles.	1	–	1	2
3 Explanations based on the movement of particles of alcohol (they pass to the gas state) when they are forced by the air movement.	–	1	4	3
4 Explanations (mainly) at the macroscopic level based on heat.	6 (3*)	7 (3*)	2*	2 (1*)
5 The surface of the table absorbs the alcohol.	4	2	3	–
6 Ethyl alcohol disappears.	1	2	–	–

Note: * They referred to particles, but they couldn't use them in their explanations.

(one from each group). They talked about ethyl alcohol particles leaving and turning to the gas state and, exceptionally, one even involved the action of air particles (category 2). For the other, a more unspecified air movement on a macroscopic scale was the cause (category 3). Half of the sample gave explanations at the macroscopic level (category 4) where heat was seen as the main agent, some also mentioning the air (but not moving). For example; 'the drop of ethyl alcohol is dried due to the heat from the surroundings' or, 'the air and the heat from the sun dry the drop'. Category 5 separates thinking on a different line; for example 'the surface of the table absorbs the alcohol', and those simply observing the disappearance are placed in the last category.

Particle ideas were much more in evidence post-intervention. Five of the pupils in C (Table 1) were again in the top category. They gave sophisticated explanations involving the distribution of energy amongst particles of alcohol, the ability of some 'high energy particles' to escape (overcoming the 'hold') and the role of bombarding air particles. The other two pupils (C and BC) placed in category 1 used ideas of distributed energy amongst alcohol and air particles, but did not mention 'hold' explicitly. Those in category 2 had taken the role of air particles on board, but not ideas of energy distribution. Nevertheless, this does begin to explain why evaporation can take place below boiling point. From the first part of the interview, two were BC and though the other was B, this version helped in thinking about the event. The third category also shows the use of particle ideas to account for the disappearance of the liquid, though the role of air is somewhat vague. Three of these were BC, two B, one AB and one A (Table 1). It seems even A can be of some value. Although, when pushed to label a diagram, the substance is indicated as between the particles, there can be a strong association with the substance. The particles model behaviour without being the substance. Similar examples have arisen in other studies (Johnson, 1998c; Papageorgiou and Johnson, 2005).

The first three categories, accounting for three quarters of the sample, all involve air as an agent at some level. The teaching had emphasised air's role, since in an earlier study pupils had paid this little attention (Papageorgiou and Johnson, 2005).

In keeping with the frequencies in Table 3, Figure 10 shows most pupils changed categories. However, those in category 5 were proportionately most resistant. It is dangerous to read too much into such small numbers, but this may have something to do with the quite different line of thinking. In a sense, it is a misreading of the event which circumvents the issue. Curiously, one pupil took up this response post-intervention.

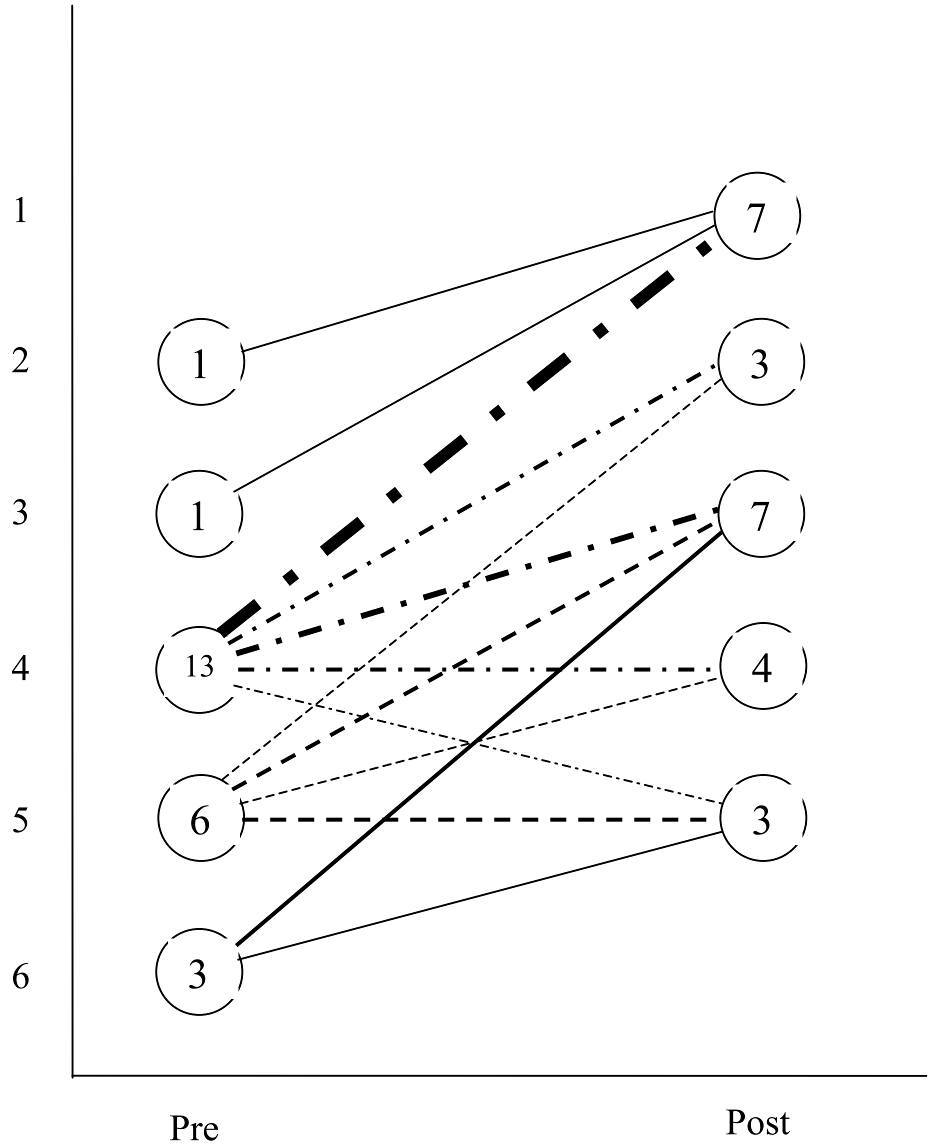

Figure 10. Changes in pupils' explanations of evaporation.

Factors affecting the rate of evaporation

Of the factors affecting the rate of evaporation, the interview addressed temperature and the substance. These allowed further exploration of the interplay between 'energy' and 'hold': temperature relating to the former and substance to the latter. Changing the surface area is just more of the same (whatever the explanation). Bringing in ideas of witnessed loss as the difference between particle rate of leaving and rate of return (which is affected by bulk air movement) was thought a step too far. Pre-intervention, the presence of an obvious agent (a lamp) encouraged a few more pupils to talk about particles of alcohol being forced out. The contrast between water and alcohol stimulated little fresh thinking. In the second interview, five (all C) of the seven in the top category of Table 3 explained the two factors in terms of the balance between energy and hold. On heating, there were more high energy particles to overcome the hold and, of the two substances, alcohol particles had a weaker ability to hold. A further five (one C and four BC, two from class T and three from class S) spoke of increased energy without explicit mention of the 'hold' for heating.

Many of the other pupils gave post-explanations bearing strong resemblance to their pre-explanations. For example, pupil 12_t:

Pre-intervention

P: Alcohol evaporates first, because it is absorbed faster by the table.
I: Why do you think that this happens?
P: Because alcohol is different compared to water.

Post-intervention

P: Alcohol evaporates first, because it can be absorbed faster by the table.
I: Why do you think that this happens?
P: Because the particles of alcohol are smaller compared to those of water.

In terms of his particle model, the pupil had moved from XA to AB (A for the gas state). Although he still misunderstands the event, the idea of different sizes makes sense and does show a use of the model which would be appropriate in other contexts.

Conclusions and implications

The pre-intervention interviews suggest well-matched samples from the two classes. Response categories were the same and arose with remarkably similar frequencies. As noted earlier, despite some previous exposure within the Greek National Curriculum, the understanding of particle ideas was largely non-existent. This could be taken as further evidence to support the inappropriateness of such an abstract model for younger pupils. However, after only six lessons, there was marked progress (Figure 8). In each group, 50% showed either a very good or some understanding of collective ideas (C or BC) and were able to apply the model to some extent in either or both melting and evaporation. Close to a further 25% had moved to a particulate view, albeit retaining macroscopic properties (B), which was of some use for evaporation. This represents an encouraging return and, we believe, endorses an introduction to particle ideas through the melting of substances (Johnson and Papageorgiou, 2007). Nevertheless, there were also illustrations of the difficulties surrounding conceptual change. For those at B or below, particles could be incorporated into an explanation without necessarily changing its basis. Pupil 12_t pre- and post-intervention regarding the role of the substance on evaporation (see above) is a characteristic example. The result is a synthetic model of explanation similar to those reported by Vosniadou and Brewer (1992) in their work on pupils' ideas concerning the earth (see also Vosniadou and Ioannides, 1998). The challenge is to use particle ideas as a means of changing pupils' explanations.

Did the software help? Given the relatively small sample size and the progress made by group T, differences are small and must be treated with caution. First, we should note that post-intervention categories were the same for both groups – there were no qualitative distinctions. Of the top two categories in Table 1, class S had a higher proportion in model C and this is reflected in Tables 2 and 3. In addition, BC pupils in group S were more successful in applying the model to the two phenomena. The biggest difference between the two groups is for evaporation with seven against three pupils in the top two categories (Table 3). Both involve particulate water and air, with category 2 lacking the more sophisticated idea of a distribution of energy. For this supposedly more difficult phenomenon, the simulation (Figure 5) might have made a particular impression and, consequently, they used it in their explanations. Overall, the software did not seem to do any harm and more likely was of benefit. We are certainly encouraged to develop it further. Here, we would emphasise that we see such software as a resource to be deployed by teachers alongside other teaching activities.

Finally, we return to the question of pupils' ability to cope with the particulate view of matter. Using our approach, in two other studies with pupils ranging from age 9–11 (Johnson and Papageorgiou, 2007; Papageorgiou and Johnson, 2005) around 50% have also achieved a promising, if not perfect, understanding. Each was a short intervention, with a different teacher, and we cannot believe this represents a limit. In the future, we need to explore the effect of subsequent interventions, perhaps specifically targeting those with lower level models. One wonders what might be achieved with a systematic, sustained approach over a number of years.

The omission of particle ideas from primary science assumes a macroscopic interpretation of changes of state and mixing has priority over a particulate explanation. Thus the following kinds of statements appear in curriculum documentation (QCA, 1998):

> In this unit children learn about the differences between solids and liquids and recognise that the same material can exist as both solid and liquid. (4D)
>
> [Note: More accurately, this applies to substances, rather than any material.]
>
> Children should learn that some solids dissolve in water to form solutions and that although the solid cannot be seen it is still present. (4D)
>
> [Note: One might question the sense in which the solute is still 'solid' when in solution.]
>
> Children often use the term 'disappear' to describe evaporation. It is important that they understand that although for example a puddle has disappeared, the water remains in the air. (5C)
>
> [Note: The QCA (a UK government agency) has produced a detailed scheme of work for Primary Science. Although carrying guidance status only, it has been widely adopted (ASE, 2006).]

However, why should a pupil recognise solid and liquid forms of a sample as being the same substance in the scientific sense? Why should a pupil think sugar or salt are still there as unchanged substances in a solution? How are pupils to understand that evaporated water remains in the air still as the substance water and with the air looking unchanged? By themselves, such 'observations' are not obvious. Their justification is constitutive of a paradigm (Kuhn, 1996) which locates the identity of a substance with a particle. Elsewhere, the QCA scheme betrays the reliance on particle ideas: 'Explain that powders flow like liquids because they have very fine particles', presupposes a particulate view of the liquid state. Or, 'Explain why filtering cannot separate dissolved sugars or salt from a solution, for example by saying the holes in the filter are big enough for the salt to go through.' Big enough for 'what' of the salt to go through one might ask? Without identifying a 'smell' with a particle (and having ideas of purity), statements such as 'Explain that we smell many liquids e.g. paint because gases from the liquid travel through the air to our noses when some of the liquid evaporates', are fraught with difficulty and virtually meaningless. What are these 'gases from the liquid'? Rather than denying particle theory to pupils, perhaps we should ask how far it makes sense to teach about matter without it.

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