Res Sci Educ (2007) 37:313–331
DOI 10.1007/s11165-006-9028-3

Representational Issues in Students Learning About Evaporation

Russell Tytler · Vaughan Prain · Suzanne Peterson

Published online: 9 January 2007

Abstract This study draws on recent research on the central role of representation in learning. While there has been considerable research on students' understanding of evaporation, the representational issues entailed in this understanding have not been investigated in depth. The study explored students' engagement with evaporation phenomena through various representational modes. The study indicates how a focus on representation can provide fresh insights into the conceptual task involved in learning science through an investigation of students' responses to a structured classroom sequence and subsequent interviews over a year. A case study of one child's learning demonstrates the way conceptual advances are integrally connected with the development of representational modes. The findings suggest that teacher-mediated negotiation of representational issues as students construct different modal accounts can support enriched learning by enabling both (a) richer conceptual understanding by students, and (b) enhanced teacher insights into students' thinking.

Key words student learning in science · representation and learning · literacies of science · evaporation

Introduction

Factors affecting students' understanding of evaporation, and how and when learning challenges might be met, have attracted considerable research interest over the last 20 years (Bar & Galili, 1994; Osborne & Cosgrove, 1983; Russell, Harlen, & Watt, 1989; Tytler, 2000). Students usually engage with this topic after learning about the water cycle, creating

R. Tytler (✉) · S. Peterson
Faculty of Education, Deakin University, 221 Burwood Highway, Burwood 3125, Australia
e-mail: tytler@deakin.edu.au

V. Prain
La Trobe University, PO Box 199, Bendigo 3552, Australia

challenges for understanding more complex scientific views about air and matter, and interrelationships of entities such as the sun, heat, surfaces, atmosphere and clouds. Following Piaget (1930/1970) and others, much past research has drawn on a conceptual change or progression approach to students' understandings, where students are expected to pass through recognizable, predictable stages of explanation. From this perspective, learning is understood as a process shaped by universal, developmental cognitive factors, while individual or group differences and preferences, and variation amongst resources available for meaning-making by learners, are considered less significant. In this paper we address directly the relationship between the conceptual and representational challenges for students in learning about evaporation.

There is also growing recognition in science education research that science as a discourse is a mix of languages entailing multi-modal forms of representation, where linguistic, numerical, and graphic and tabular modes are integrated to represent scientific explanations (Ainsworth, 1999; de Jong et al., 1998; Dolin, 2001; Kress, Jewitt, Ogborn, & Tsatsarelism, 2001; Kress & van Leeuwen, 2001; Stenning, 1998; Unsworth, 2001). At primary school level students need to be introduced to multiple and multi-modal representations of science concepts and be able to understand, translate and integrate these representations as part of learning the nature of scientific knowledge, inquiry, and reporting. Multiple representations refers to the capacity of science discourse to represent the same concept or process in different modes, while multi-modal representation refers to the integration of different modes to represent scientific processes, findings, and explanations. In summary, these new accounts of the nature of learning science, and factors affecting this learning, imply the need for teachers to focus on more than cognitive factors, such as the likely sequential reasoning practices of students, in teaching the topic of evaporation.

In this paper we draw on the literature outlined above to provide an interpretive lens for analysing one upper primary school student's engagement in a classroom program on evaporation. The research questions guiding the study were as follows:

(1) What representational challenges do students experience in engaging with particulate accounts of evaporation?
(2) In what ways can this focus on representational issues contribute to current understandings of students' conceptual learning?
(3) In what ways does an explicit focus on representation enable advances in learning (In particular, what affordances does engaging with the representation of a molecular model offer Grade Five students' understanding of evaporation)?
(4) What are the implications for teachers' understandings of students learning science, and for classroom practice?

We first review the literature to identify key interpretive issues before presenting an account of the particular program, its rationale, goals, classroom strategies, and the pre- and post-instruction understandings of evaporation demonstrated by the students. While we report briefly on results of nine Grade 5 students as part of a larger class, one child's learning is analysed in detail. This approach has been undertaken to enable us to represent the considerable intricacies entailed in negotiating and extending representational meaning with children. This case is not presented as a typical or exemplary one, but rather seeks to foreground the distinctive and individualistic nature of students' engagement between children's own meaning-making processes and the representational resources of science. Several theoretical and practical implications for effective classroom practices are then considered.

Literature Review

Past research into students' understanding of evaporation, drawing on Piaget (1930/1970), has tended to focus on explaining students' learning in terms of a developmentally based progression in conceptions (Bar & Galili, 1994; Bar & Travis, 1991). Piaget's discussion of students' reasoning about causality at ages 9 and 10 did not directly address the topic of evaporation, but could be seen to lend support to the value of a developmental view of cognitive readiness for learning about this topic. He noted that students at this age consider every substance to be composed of material that is "more or less condensed or rarefied" (1970, p. 265), and that substances are "made up of particles tightly or loosely packed together" (1970, p. 266), thus implying that students have some appropriate ontological ideas or categories for engaging with a scientific explanation of evaporation. He also claimed that students at this age start to develop a sense that "a series of intermediaries" (p. 269), or sequence of processes in time, might intervene between a cause and its effect, thus enabling students to entertain more complex scientific accounts of the interactions between the sun, heat, water and surfaces. For Piaget (1970, p. 269) a further development in students' understanding of causality is the "progressive establishment of reversible series," indicating that a reversible mechanism can explain an effect. For example, from this perspective the water cycle can begin to be understood as a series involving water, evaporation, clouds and rain. Piaget (1970, p. 275) also noted that students often sought to eliminate chance from nature, "for everything admits of justification or of motivation, since everything in nature has been willed." In this way, he argued students were likely to find an over-arching reason for a range of facts that adults consider "fortuitous and contingent" (p. 275). Again, such a perspective might provide an insight into students' explanatory constructs and likely ideas in relation to evaporation and condensation.

Drawing broadly on a Piagetian orientation, researchers have sought to explain students' difficulties and misconceptions in this area, as well as identify stages in students' conceptual readiness to understand this topic. Difficulties were perceived to involve the transfer of macroscopic properties such as expansion on heating, to the microscopic domain. Students' reluctance to use the idea in their explanations (e.g., Driver, 1985) has been held to lie in the abstract nature of the particle model. There is also evidence of ontological difficulties with the idea of particles (e.g., Scott, 1993). Bar and Travis (1991) and Bar and Galili (1994) claimed to identify four distinct stages in students' progression in understanding evaporation and condensation: water disappears, water is absorbed into surfaces, water is transferred upwards, and water disperses into air. They associated the transitions between stages with particular ages, with the highest stage occurring at about age 13. In these studies, students' conceptual progression is empirically established, and largely explained by appeal to the inherent abstraction of the higher level conceptions (such as the difficulty of imagining water held, invisibly, within air). However, the stability and sequential nature of these conceptions have been questioned (Tytler & Peterson, 2001, 2004), signalling a need to rethink the value of this framework in capturing students' thinking. Various other reviews of the literature on students' understanding of evaporation, including Driver, Leach, Scott, and Wood-Robinson (1994), P. Garnett, P. Garnett, and Hackling (1995) and Tytler (2000), indicated both strengths and limitations to a Piagetian orientation. Other researchers, such as Johnson (1998a, 1998b, 2005) and Papageorgiou and Johnson (2005), argued that particle theory is critical in supporting satisfactory representations of evaporation phenomena such as water boiling, because without particulate ideas, the notion of the liquid–gas transition cannot be successfully imagined. Novak and Musonda (1991) and Novak (2005) provided evidence that the introduction of a particle concept at an early age was of great importance for students' future understanding.

More recent research into the general goals of, and factors affecting, learning science has questioned the value of a narrow conceptual focus in interpreting students' developing understandings. There have been calls to include epistemological dimensions of learning, students' reasoning strategies and their views on the nature of science in accounts of learning (Driver, Leach, Millar, & Scott, 1996; Duschl & Gitomer, 1991). Researchers such as Strike and Posner (1992) and Pintrich, Marx, and Boyle (1993) have drawn attention to the role of students' personal beliefs, values and attitudes, and contextual factors within different classrooms, as influential in students' conceptual learning. Others researchers from sociocultural perspectives, such as Alvermann (2002), Gee (2002, 2004), Hennessy and Murphy (1999), Lemke (2004, 1998), and Tytler and Peterson (2001, 2004), have focused on the need to consider both the representational practices of science communities and the diversity of learner resources in engaging with these practices as influential in effective learning. These resources include cognitive (memory, observational skills, reasoning), linguistic, motivational, dispositional capacities, as well as social and cultural orientations, that influence students' abilities to build explanations and engage with the representational practices of science.

A recent strand of research in science education has focused strongly on the representational demands of this subject as a crucial aspect of learning. From this perspective, students need to understand and conceptually integrate different representational modalities or forms in learning science and learning how to think and act scientifically (Ainsworth, 1999; de Jong et al., 1998; Dolin, 2001; Karmiloff-Smith, 1992; Kress, 2003; Lemke, 2004; 1998; Roth, 1995; Russell & McGuigan, 2001; Stenning, 1998). While various classifications of these modes have been proposed, there is broad general agreement that these forms, for the purposes of learning science in primary and secondary school, include such categories as descriptive (verbal, graphic, tabular), experimental, mathematical, figurative (pictorial, analogous and metaphoric) and kinaesthetic or embodied understandings or representations of the same concept or process. Kinaesthetic or embodied understandings refer to a growing research literature on the role of gesture and physical action in learning (Goldin-Meadow, 1999; Goodwin, 2000; Roth, 2004). There is a broad consensus in this expanding literature on representation in science that students need to develop an understanding of diverse modes, rather than be dependent on particular modes for specific topics, if they are to develop a strong understanding of how to use and represent science concepts. Current science teaching practices incorporate the use of both authorised or justified representations as well as student-generated multiple and multi-modal representations for some topics (such as the use of 3D models, diagrams, verbal accounts, role-play, and CD-Rom illustrations for teaching topics like the solar system). At the same time, there is a growing recognition of the need for students to learn how to interpret, integrate, and reproduce multi-modal representations within and across topics if they are to develop understanding of a science topic, as part of a broader science literacy.

The relationship between concepts and their representations has a long history in the philosophical literature. We would argue, following Peirce (1978) and others, for a triadic model of this relationship generally, and in learning in science in particular, where distinctions can be made between a concept (for example, the idea of evaporation), its representation in a sign or signifier (verbal and diagrammatic accounts of evaporation), and its referent, or the phenomena to which both concept and signifier refer (changes to states of matter in the world). Each part of the model is distinguishable from one another. For example, a particle diagram has material features such as its conventions, clarity of image, and size, that are not reducible to its conceptual meaning, and learners are expected to recognize the differences between an idea, the different ways this idea can be represented, and the phenomena to which it refers. However, as noted by Peirce (1978, p. 339), “the meaning of a representation can be nothing but a representation.” This implies that all attempts by learners to understand or explain concepts in science entail representational work in that they have to use their current cognitive and representational resources to make sense of science concepts that are new to them. Understanding the idea of evaporation cannot precede its representation, and in this way cognitive capacities within the subject-specific domain of science are dependent on the current and potential representational tools available to learners. In this sense, neither evaporation nor molecules can be conceptualized separately from some form of representation, although each can be represented in different ways. This implies that the epistemological question of coming to know what the terms evaporation or molecules mean as both concepts and words must entail understanding and using the appropriate representational resources to make cognitive links between appropriate phenomena and theoretical accounts of this phenomena. Therefore learning about new concepts cannot be separated from learning both how to represent these concepts as well as what these representations signify. We would further assert, following Ainsworth (1999) and others, that conceptual understanding is strengthened where students learn to recognize the same idea, or different aspects or further implications of the same idea, across different representations or different modes of representation, noting that these cross-representational concepts or ideas only exist in further, new representations.

Drawing on these research literatures to guide interpretation, our paper reports on a classroom program that sought to engage students with science concepts relating to evaporation. The students were expected to develop an understanding of this topic through interpreting, constructing, and integrating various representational modes such as diagrams, verbal accounts, gestures, and captioned drawings relevant to key inter-related concepts in the topic. This engagement entailed students (a) clarifying their thinking through exploring representational resources, (b) developing understanding of what these representations signify, and (c) learning how to construct and interpret scientific representations about evaporation.

Research Design

This study used a qualitative methodology (Denzin & Lincoln 1995) to analyse one child’s response, as part of a larger study of nine students, to a lesson sequence on evaporation with three grade 5 classes (age 11) in an Australian primary school. The sequence was followed by two interviews spaced a year apart, with nine of the students who have been involved in a longitudinal study (Tytler & Peterson, 2004, 2005). A sequence of classroom activities was devised to provide an instructional context in which students’ ideas were probed and challenged. As part of this sequence a molecular model was introduced as a potential representational resource and explanatory framework, and classroom discussion focused on using this to interpret aspects of phenomena such as boiling water, condensation, and the distribution of eucalyptus oil scent around a room. Students were asked to interpret these phenomena using diagrammatic representation, written captioning, and verbal explanation, and to integrate these representations. The sequence is described in more detail elsewhere (Tytler, Peterson, & Prain, 2006).

In the follow up interviews, nine students were presented with a variation of these activities and asked to represent them in different modalities, and challenged by the interviewer to elaborate and refine these representations and their conceptual meaning. The students were interviewed a year later, using similar tasks. Transcripts of the interviews were analysed to explore the links between learning and negotiation of representational meaning. This study builds on a longitudinal study of one of the students, Calum, involving exploration of his science ideas each year from the first grade at school. Thus, we had information on his thinking about evaporation prior to this study, and the nature of his approach to learning.

Introducing the Molecular Representation

At the start of the sequence students filled in a questionnaire, using drawings and annotations, concerning their explanations of a number of evaporative phenomena. Following this, the researchers conducted a lesson in each of the three classrooms. This consisted of a whole class orientation activity in which students watched a frying pan of water boil, Following this, one of the researchers presented the class with a model consisting of plastic beads in a Perspex tray, which was used as the basis of a discussion on evaporation involving molecules of water breaking free of the surface and going into the air. This was discussed firstly using the beads, and then constructing a drawing which depicted water boiling in terms of molecules of water changing to a gas (spread out molecules) in the bubbles. The molecular model underlying these representations was presented as a scientific idea the students might find useful in thinking about these phenomena, and the language used was relatively open so students would not feel they were being presented with "one true perspective". The discussion attempted to model the productive interplay that can occur between different representations: pictorial, physical, verbal and gestural.

Following this discussion, students worked in groups on three successive activities representing different evaporative contexts (condensation on a cold can, a disappearing handprint involving a wet hand placed on a towel, and a class activity in which a bottle of eucalyptus was opened in the front of the class and students asked to explain the patterns of scent that occurred round the room). For each of these activities students were asked to write on a worksheet an explanation of what happened. There were follow up activities run by the teachers in the subsequent week, including observation of a puddle drying up (for which students drew their interpretation – this was available in the interview), charting the diminishing water level in a jug of water over a week, and an experimental activity involving exploring the conditions controlling the speed with which wet clothes might dry. From talking to the teachers after these sequences, and from the interviews, it seemed that no strong or coherent view of evaporative explanations was established across the classes.

The intention in introducing particle representations was to provide students with a way to (a) make connections across different states of matter in the evaporative process, (b) imagine how water can exist in air, and (c) understand the various associated effects of the evaporative process. In the discussions surrounding the lesson activities, we noticed a tendency for the students to over-determine the actions of molecules. In the subsequent interviews we focused specifically on representing molecular distribution.

Nine students who are part of a longitudinal study (Tytler & Peterson, 2005) were then interviewed individually concerning their views of evaporation, among other things. After the program the students were asked evaporation questions related to their interpretation of the sequence based on their written responses to the worksheets, and probing their views concerning the evaporation of a drop of alcohol, placed on a glass slide, and also on a silk cloth. They were asked to draw, as if through a powerful microscope, what was happening to the alcohol drop on the slide, and also to represent in a drawing "where is the alcohol now?" (see Fig. 1)

One year later, these students were again interviewed about, among other things, alcohol evaporating and condensation in a terrarium. This interview was intended to probe whether subsequent learning had taken place, or if insights had been lost.

We have been working with teachers at the school for a number of years now, and running such lessons prior to interviewing students. The principle we follow is that we generate rich experiences and productive and challenging discussions, but we do not present ideas in a way that implies a resolved view on what explains the phenomena. Ideas are treated as always in process. We have been tracking students' ideas on a range of scientific conceptions and in particular have followed their views on evaporation since the

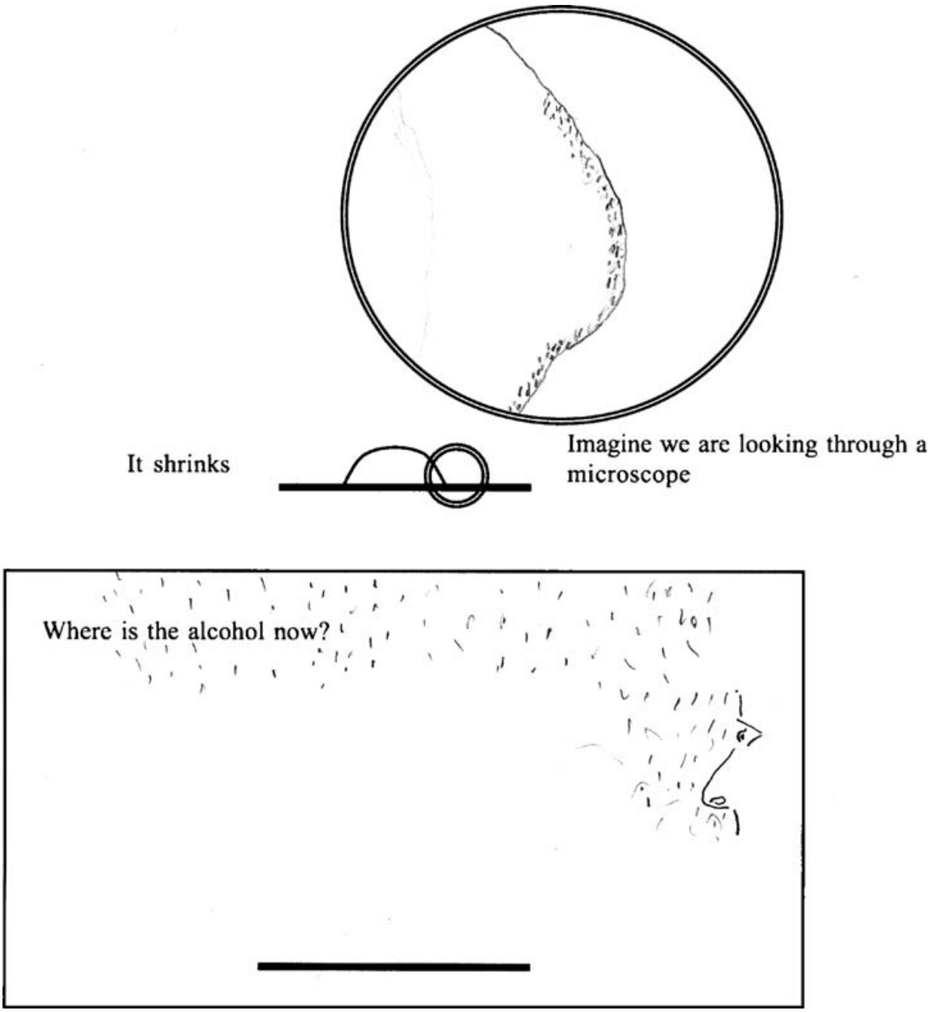

Fig. 1 Calum's first interview drawing of the alcohol evaporating

first year of school (Tytler & Peterson, 2004). On this occasion, given the students are age 11 and entering an interesting phase where they are beginning to be exposed to canonical versions of science, we resolved to expose them to a particle model as a useful explanatory resource, to examine more closely the extent to which it would be taken up, and the challenges and opportunities it would present. The scientific account of evaporation is highly spatial and visual, drawing on notions of molecular movement, spatial rearrangement, and distribution in air. It thus afforded us the opportunity to look more closely at the relationship between these different representational modes and the issues involved (affordances and constraints) in translating between them.

The data sources considered for this paper come mainly from the interview with one child, Calum, and specifically from those parts of the interviews in which he was representing the evaporative phenomena using different modes, mainly pictorial and verbal. The students were questioned concerning the meaning of their drawings, including the drawing they had made of the disappearing puddle as if through a microscope.

The interviews were transcribed and analysed, and the students' drawings collected and interpreted.

Notes from the Introductory Lesson and Interviews

The students' responses during the sequence will not be considered in detail in this paper. In the first lesson taken by us, the views expressed through worksheet responses, and also observed, were broadly consistent with conceptions of evaporation previously reported in the literature. However, a number of points arose concerning students' capacity to engage with molecular representations.

In the molecular presentation the discussion was sufficiently lively in each class to indicate they were able to engage with the idea. They did not, however, tend to use the idea in explaining other activities. The discussion of the wet handprint, for instance, and the written explanations, indicated a strong absorption explanatory narrative was triggered by perceptual cues inherent in the phenomenon.

The eucalyptus oil activity, because it was carried out with the whole class, enabled us to focus students' attention on molecular ideas as possibly helpful to explain what was going on. Students were able to talk readily about the eucalyptus smell moving through the room. In most cases the spread occurred predictably. In one of the classes, however, it appeared to register round the room more haphazardly, possibly because of differing sensitivities or breezes in the room. When asked to think about how the molecular model might be used here, students mostly talked about the molecules coming from the oil to their noses, as though in a direct path without appeal to a sense of distribution. One boy claimed to have smelt the oil from the back of the room earlier than most, and students talked of the molecules jumping over heads to reach his nose. There was talk of molecules "zig zagging" to explain why the pattern of people smelling seemed random. It was as if students were proposing some causal intent to the molecules themselves. They seemed to be over-determining the molecular movement and its relationship to the pattern of smell, overlaying a direct causal argument on to a model that implied a causation based on the distribution of the collective, underpinned by an essential random movement of molecules. Thus, we resolved to look more closely at Piaget's ideas of causal thinking in students, and to probe these ideas more closely through the interviews. These explicitly flagged the idea of molecules as an explanatory framework.

During the interviews, which in effect formed part of the learning sequence because of their interactive nature, the students discussed their classroom generated representations of the puddle evaporating, and went on to represent and discuss a drop of alcohol disappearing. Across the class more than 80% of students had used molecules in their puddle explanation. Not unexpectedly there was a range of interpretations of the nature of molecules. Some associated molecules with bubbles, or had them exploding or dissolving or evaporating into the air. For many students there was a strong overlay of water cycle imagery (see Tytler et al., 2006). It seemed likely that their inclusion of molecules in the drawing was the result of explicit teacher encouragement, with the molecular model sitting within a water cycle conception as a transfer mechanism. In the interview students were challenged to elaborate on these and subsequent representations, with the explicit aim of exploring the possibility of constructing a causal account of the alcohol smell based on the spatial distribution of molecules. We argue that the interview in this study provides an instance of teacher mediated negotiation of representations which had been introduced in the classroom sequence. The interviewer, in Vygotskyan terms, plays a role of knowledgeable adult, scaffolding students' use of their representations to achieve a coherent explanatory narrative.

Four of the nine students arrived, through this negotiation process, at a scientifically acceptable representation of particles distributed in the air, allied to a coherent narrative account of the alcohol evaporation process. However, each of these emphasised different causal elements that, because we have considerable longitudinal data on each of the interviewed students, we would argue reflected their particular interests and narrative styles (Tytler, Peterson, & Prain, 2006). The other students to various degrees represented the smell with 'wafting' lines, or imposed a strong water cycle imagery on the particle representation and explanation. In the second interview, the idea of distribution was more readily entertained. For each student, the process of representational negotiation was generative and enabled them to achieve more coherent explanations, and at the same time clarified for the interviewer the nature of their conceptual difficulties. The story of these students' learning is thus complex, and sits within a history of explanatory accounts of evaporation and other phenomena. In order to tease out the nature of the advances in understanding attending this focus on particle representation, we have chosen to present the detailed learning story of one student, Calum. While Calum's story is not formally representative of the other eight students, the interactions between his previous history, the representational focus, and his learning during the sequence including the interviews, are broadly representative of what happened with each of the students.

Case Study: Calum

We have selected one case to report in some detail the connections between accessing and negotiating a molecular representation, and learning. The case was selected because Calum demonstrated strong and diverse connections across different representational modes, thus providing rich data for interpretation. Other cases were rich in different ways (Tytler et al., 2006), but the thrust of findings concerning learning pathways and gains are repeated for most of the students.

Calum is a child who has a history of interest in science from before he started school. During the course of the longitudinal study his ideas on evaporation shifted as he became able to construct coherent narratives that traced what happened to water when it evaporated, and related these to events from his personal life in ways that showed a commitment to ideas and interest in constructing deeper explanation. Calum tends to push for narrative accounts of phenomena that make sense of underlying mechanisms, and focus on details of phenomena to make sense of what is happening. His history of evaporative ideas is described in some detail in Tytler and Peterson (2004). By Grade 2 he consistently used water cycle imagery to talk about evaporation, and in Grade 3 made the advance of talking about water being taken up into the air.

> It's like when a puddle evaporates and it goes into the cloud but there's not clouds cos we're in a room here, so it just becomes a part of the air... water that's evaporated. And it rises up.

In the same interview, he describes what happens with a damp tea towel:

> umm... the sun would have evaporated it and just like the puddle... um, the same thing would have happened and since it would've been outside on the line, it would've gone up to the clouds and then go down as the rain.

Thus by Grade 3 Calum had made the advance over a water cycle notion of water going up through the air to the sun or clouds, to realise the local role of air in holding water, at least as a temporary station, while doors and windows are shut, on the way to clouds. He consistently demonstrates this. He seems not to have a detailed view on just how water can exist in air.

In the prior knowledge probe at the beginning of the Grade 5 sequence, his explanation of the water level in a fish tank dropping is consistent with this insight: "It slowly was evaporated from the heat and eventually will rise to the clouds." At no point up to this had he entertained the idea of a particle interpretation.

In his written accounts, during the first lesson, of condensation on a cold can, and the eucalyptus oil smell, he uses the idea of molecules, particularly to explain the "gathering" involved with condensation: "the ice is cold on the inside and the monocles (sic) on the outside are warmer. The hot monocles are sucked to the cold and the monocles gather." This is the first time we are aware of Calum developing a mechanism for explaining condensation, and arguably is an advance made possible by the molecular representation. In explaining the disappearing puddle, presumably based on the classroom development of a molecular representation, Calum's written account overlays the water cycle imagery with a molecular representation: "The heat makes the monocles (sic) jump into the air the hot air rises and takes the monocles with it ... to the clouds." Calum's verbal account in the interview confirmed and elaborated his pictorial and annotated representation. His verbal account of evaporation relied strongly on a process of constant referral to comparative cases, in this instance the relative speed of evaporation. For example, in explaining the disappearing puddle, he offered the following commentary:

> The heat comes off the sun and the water on the ground has...is being evaporated slowly, probably more slowly than in a...probably faster than in a jug or...but slower than in a frypan... And it would rise up with the heat and go up to the clouds probably straight away. 'Cause we were outside. And also a few people were in the shade...

While he was confident he could extend the water cycle image to include movement of molecules, he was still uncertain about the details of their spatial distribution. When probed about the relationship between the molecules and the definite edge in his diagram, and what was in between the molecules, he responded tentatively with "Ah, maybe air."

In drawing the evaporative process of a drop of alcohol during the interview, his representation of molecules clustered round the drop's edge closely matched his previous drawings for a puddle. When questioned about this, he explained that the evaporation would primarily occur at the edge since the water was deeper in the middle of the drop.

He accounted for what happened to the molecules in the following way:

> Ah, I have been saying the whole time the heat makes them kind of sizzle and they kind of are sucked or kind of jump a little bit into the air and when that happens the low...the temperature would um, kind of rise up and bring them up with it.

Calum accompanied this oral account with a gesture, using his hands to indicate an upwards clutching process, representing the agency of the heat or temperature. In this way he attempted to construct and consolidate an understanding by integrating verbal and gestural representational modes to supplement his pictorial account. In this case the gesture could imply a causal account of the agency of heat (from the sun, and from hot air rising) in the evaporative process. Whether such gestures can be generally characterized as pre-linguistic understandings, as proposed by Roth (2004) and others, remains an open question that needs further investigation.

At this point in the interview a detailed discussion developed between the interviewer and Calum, based on his representation of "where is the alcohol now?" (see Fig. 1) in which he continued to draw and talk in response to the interviewer's questions. He was asked where the alcohol is now. He implied it slowly rises to the ceiling. (C draws dots near the top of the frame).

Interviewer: Do you think it only goes up or would it spread out as well?
Calum: Ah, yeah, it would spread out and kind of...'cause otherwise if it just went up like, eventually when it was up near the roof it would be kind of be like just lumped together and that's not what really happens. So it kind of just all spreads out.
Interviewer: OK. And the fact that you could smell it when we put the drop on...how would you explain that? What's happening with it that makes it possible to smell it?
Calum: Well I think probably each molecule has kind of like a little scent that's the same scent and sometimes maybe you can...they just let off a scent, each molecule ...
Interviewer: So, the molecule, where would it be ...when you were actually smelling ... let's say I was to draw a nose (draws nose: see Fig. 1) ... what would you draw in order to show that person smelling the alcohol?
(Calum draws dots and lines around the face and nose)
Calum: Well all the molecules would go around and float around the room and saturate the room and when it comes past you, you can smell it and...
Interviewer: It wouldn't go up your nose?
Calum: Ah, well they might. A few might if you breathe in through your nose.

During this interaction, Calum was challenged to be more explicit about his understanding of the distribution of molecules. The drawing provides an explicit shared reference point for a collaborative process of clarifying and elaborating ideas. There is a complex interplay between the verbal account and the emerging drawing as a means to consolidate Calum's understanding. The requirement to represent his emerging understanding visually in the context of the interviewer's probing challenges him to clarify the adequacy and consistency of his ideas. This interplay also provides insights for the teacher/interviewer into Calum's sense of the molecular distribution as well as his understanding of the role of molecules in the act of smelling.

His responses indicate a tendency to over-determine the relationship between molecular movement and individual experience of smelling the alcohol ("when it comes past you, you can smell it"). Through this integration of discussion and pictorial production, Calum has reasoned his way from a simple picture of alcohol molecules moving upwards to the top of the room, to a more distributed view that explains why the alcohol can be smelt. This seems to be a shift from an upwards water cycle view of molecular movement, to a more complex appreciation of their distribution in a room. While this exchange between the student and interviewer does not necessarily demonstrate that Calum has a clear and durable knowledge of this distribution, his responses suggest that engagement with the representational task has deepened his understanding of (a) the topic, and (b) the challenges in attempting to represent this distribution pictorially.

A year later, in the interview dealing again with a drop of alcohol, Calum has retained his commitment to a molecular representation, voluntarily introducing the idea when prompted to say what you would see with a powerful microscope.

Interviewer: Can you tell me a bit about the molecules, what do you know about them?
Calum: They're tiny drops of water that actually make up water and when heat is like over the water the hot water rises and it takes the top layer of molecules with it.
Calum draws little circles representing the edge of the drop (Fig. 2). His focus on elaboration of a mechanism is consistent with the previous year, as is his view that heat and hot air rising takes the molecules up. He was in fact uncertain about the nature of the relationship between the substance, alcohol, and the molecules ("I am not sure if they would be alcohol molecules ... after the molecules came up, the little particles would be left"). However, his concern for where the molecules go, prompted by the conversation with the interviewer centred on the representation sharpens his sense of how alcohol might exist in air, and the implications of the spatial distribution.
Calum: It would probably be gone up here like where the hot air rises to here and if you had it in here, because they can't go very high up and there's much space for it go it will just gather again.
Interviewer: So you are drawing the arrows here, is that the hot air rising?
Calum: Yes and taking the molecules up. (Those little dots) ...they're the molecules.
Interviewer: You have only drawn two.
Calum: They are pretty much like spread out (he draws more)
Calum's drawing (Fig. 2) separates out the molecules from the wafting mechanism of the air. He is combining two pictorial sign systems, one dealing with the distribution of material, the other with movement of air that carries the molecules.
Calum: You would smell their scent while they were being taken up by the hot air.

Again the interviewer inserts a nose into the drawing. Calum draws wafting and circulating patterns near the nose. In this process the drawing is used to co-construct with the interviewer a sense of Calum's emerging understanding of spatial distribution and random movement. His confusion about the molecular nature of air and alcohol, and their relationship, is apparent in the drawing, because they are represented differently.

Calum: In the nose there is little ... scent glands and you might even, when you are breathing kind of breathe the air and the that might bring the air closer to your nose and you could smell more.

So it should go up like this in the hot air, but if you just (inaudible) some of them just might go closer to your nose.
Interviewer: So those wavy lines is the air hotting up in a little circle ... how do you imagine the air looks like in there, is that made of molecules or is there something ...?
Calum: I am not sure, its oxygen, like a kind of gas, so I am not sure if they are molecules or not.

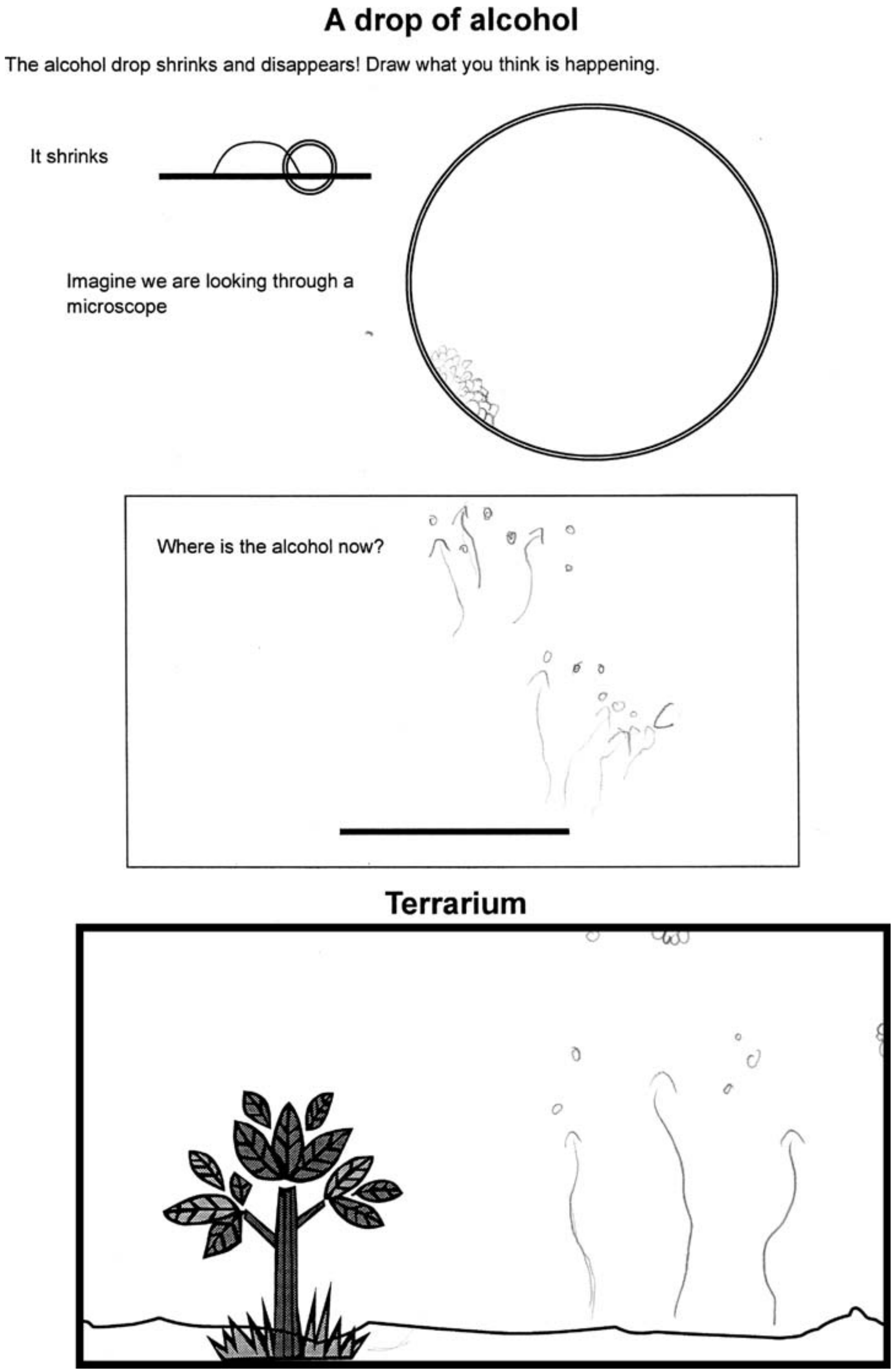

Fig. 2 Calum's second interview drawing of evaporating alcohol

At this point Calum seems to harbour a few non-standard conceptions of molecules, being separate from the smell and possibly from the substances as such, and has a view that air may not be molecular. However, he is developing a sharper view of the spatial distribution, in coming to terms with the nature of the phenomenon.

At this point in the interview the discussion turns to a terrarium, which these children have investigated previously. It has a plastic lid with clear signs of condensation. In discussing the terrarium he uses the notion of molecules to sharpen his previous accounts, which were based on the water cycle, by now suggesting a quite detailed mechanism for the cycling of water in the terrarium.

Calum: And the molecules would have been on the leaves or most of them would have been absorbed by the leaves, but as you can see mainly on the walls they have been taken up and since there is not much space in the terrarium they just have to stop on the roof and because they would all go on the roof except the ones that have been absorbed they sort of start to gather again to make actual drops of water.
The interviewer probes, through a verbal and gestural interchange, details of Calum's explanation.
Interviewer: So you are imagining the molecules that go up into the air they gather on the surface to make drops, what would happen then?
Calum: It would probably just drip back down.
Interviewer: Then when the sun warmed it up what would happen then?
Calum: It would definitely be evaporating.
Interviewer: And what would you see then?
Calum: You would see then the molecules gathering again.
Interviewer: Could you just draw for me, that is the terrarium there, that's the plant, just draw for me what happens to the water?
Here Calum develops, in the drawing, a representation of this "clumping" action. The use of the molecular representation enables condensation to be envisaged in some detail.
Calum: When the heat comes in it takes the air that is left in there, the hot air rises and it takes the air and the little molecules up and up and eventually they all start to gather there and once there is enough of them there they become easier to see and then they drip back down the wall.

Calum has achieved, through the representational possibilities of the molecular drawings, a sharpened sense of distribution and mechanism for water and alcohol evaporating. His advance represented by the first interview has been retained, and built upon in the second, through the mechanism of representational co-construction with the interviewer. His account of the terrarium is indicative of his knowledge gains in that he can now coordinate a visual representation of evaporation with a coherent explanatory narrative of this phenomenon.

Representation and Learning

Calum is one of nine students who were interviewed and for whom we had detailed information about their past history of evaporation explanations. These students generally have a history of development of their ideas about evaporation to the point that they are all confident with a water cycle image, and in some cases can talk about water being held in the air, or coming out of the air in condensation phenomena (Tytler & Peterson, 2004).

These ideas are reflected in the prior knowledge questionnaire in this sequence, and in most cases their written responses to the first lesson activities indicate a grasp of this understanding but little confidence with using the idea of molecules. What is added, in the conversations based round the interview drawings, is a closer sense of local distribution that is used to explain details of the smell phenomenon, and encourages thinking about the mechanism of dispersal into air. We would argue that there is a shift in their capacity to imagine the process whereby water can exist in air, that involves the construction of a narrative of causation allied with the spatial representation. Calum's history demonstrates his interest in science and his willingness to use a range of representational modes to construct explanatory causal narratives. His case study is not presented as typical of students' responses. Other students in the program varied considerably in their interest in, and capacity to, engage in these processes. However, we would argue that his case demonstrates necessary links between effective science learning and negotiation of representational modes and meaning. We chose to present Calum's case as a rich account of these processes.

All the interviewed children were able to engage in varying ways with the representational demands of the topic. There were interesting variations on how the movement (wafting, air currents, general directionality) was represented and explained. For Calum, heat continues to figure as an important causal mechanism (see Andersson, 1986). Other children drew wavy lines to represent the wafting of the smell. Thus, students' understandings of this complex of features contains a range of pictorial elements dealing with different explanatory dimensions: descriptive (such as arrows showing the direction of movement of the vapour) causal (such as focusing on heat or hot air rising) and material (exploring the change in location and circumstance of the alcohol or water).

We do not argue for a promotion of standardised representations (such as happens in primary schools, for instance, with the water cycle) in supporting students' learning. Each child's representations were different in significant ways. Rather, our view is that we should treat representations as epistemological tools through which students can explore science ideas and clarify for themselves their understandings. The complexity of challenges these children faced in representing evaporative phenomena would argue against the possibility of achieving a resolved conceptual position. Rather, various representations that comprise different aspects of the process should be seen as individually constructed and ultimately "in process". What matters in learning is not a tightly determined end point, but the quality of the process of developing and refining ideas.

Implications

Analysis of the lesson sequence and the case studies suggests that there is a range of learning challenges for students in engaging successfully with a particulate theory of evaporation. While our study may seem to confirm the research literature on the demanding conceptual challenges for students in understanding such a theory, we assert that such a conception can be generatively explored with 11 year-old students and readily implanted into a water cycle notion. Further, we assert that the challenges for students in engaging with this topic are both conceptual and representational, and that these challenges are indivisible. One conceptual challenge lies in the notion of distribution and chance as causal. Students' understandings at this age are readily over-determined by a simple causal view of the movement of molecules, as noted by Piaget (1930/1970). For example, the students' drawings of evaporation often echoed a highly determined pattern of movement associated with their prior understandings of the water cycle. In discussing the smell of eucalyptus oil, there was talk of molecules "zig zagging" to explain why the pattern of people smelling seemed somewhat random. In the interviews the conceptual problem became apparent as a representational issue, with some students, in attempting to represent this pattern in a drawing, wanting to indicate a causal pattern based on localised interactions of particles with the nose.

Difficulties previously found in the literature, concerning imagining the relationship between molecules and the substance itself, or confusing categories of smell, or heat, or air, and substance, while present here, did not interfere with a productive engagement with spatial representations of the evaporative process. In fact, this connected use of visual and verbal modes to represent science understandings brought to the surface various "misconceptions," in a way that would allow them to be fruitfully clarified and refined through further representational work.

It has been argued that molecular ideas are too difficult for young children because of this complexity of causation and distribution and properties that they embody. However, molecular ideas can be used at many levels, and in this study we have introduced them to help students visualise a particular problem with evaporation – how water might transform, and exist imperceptibly in air – without attempting to complicate the issue by focusing on surface mechanisms or molecular properties. Thus, it is a particular representation of particles, and a particular causal logic, that were introduced and which provided the representational challenge for these students. We would argue that the complexity of envisaging particles beyond this is not relevant to examining the affordances, and constraints, of this representation for evaporation. Papageorgiou and Johnson (2005) argue that a particle model is advantageous in helping students explain changes of state and dissolving, even where a sophisticated version of the model is not achieved. However, they tend to ignore the complex representational work students need to undertake to secure these gains. Johnson (2005) argues specifically that a particle model enables students to imagine what is happening with evaporation, In this paper, we are further arguing that this imagining fundamentally involves students developing appropriate representational resources related to particle ideas. Our findings differ from those of Bar and Travis (1991) and Bar and Galili (1994) in that we are arguing that children in upper primary school can begin to understand a particulate explanation of evaporation. In this regard our findings confirm Piaget's views on the capacity for children to imagine the particulate nature of matter, and to understand the idea of reversible states. However, our study suggests that teacher-guided negotiation of how this particulate explanation can be represented can also extend students' understanding of the distribution of particles.

From a sociocultural perspective, our study indicates that Calum's capacity to engage effectively with the representational practices of a science community, here instantiated in the perspectives and representations of the researcher/interviewer, are highly influenced by Calum's history, his sense of self, and his particular learner resources. His cognitive (memory, observational skills, reasoning), linguistic, motivational, and dispositional capacities, his pleasure in identifying mechanistic causal over-arching explanations, and his sense of himself as successful in this area of the curriculum, all influence his responses to, and engagement with, these tasks. In retrospect, we would also argue that Calum's history of engagement with ideas in science could be seen as involving a representational flexibility, in which he has tended to search out ways of linking ideas using a variety of diagrammatic, verbal and kinaesthetic representations to speculate and construct explanatory narratives. Our study also confirms the extensive literature cited earlier in this paper indicating that learning science necessarily entails the capacity to link conceptually different representational modes. What our study highlights is the significant complexity of this negotiation of meanings across modes, and the crucial role of the adult/science initiate in providing timely scaffolding and responsive feedback in developing students' understanding.

There is evidence in Calum's case study that his engagement with a molecular view of matter, and its representation, enabled him to imagine how water could be contained in air, details of mechanisms for evaporation and condensation, and the implications for phenomena such as dispersion of smell, and the location of vapour in a room. This case study suggests that for the specific issue of molecular distribution the negotiation of meaning around visual representation was particularly enabling. The study also indicates that this process of representational negotiation provides key insights into student thinking. The pedagogical implications of these assertions align with Vygotskyan, rather than Piagetian views of learning, given the focus on teacher support for students to develop and refine their representational resources. Our study suggests that learning about evaporation is not simply a story of cognitive readiness, but could entail extensive highly focused opportunities for teachers and students to negotiate appropriate representational tools for exploring this topic.

The idea of molecules with distributive properties becomes a powerful representational tool that enables students, with support, to develop explanations of details of evaporative phenomena. In terms of the classic conceptions literature, this study has illustrated previously described difficulties with the molecular notion. However, taking this representational perspective has shown how the idea can open up explanatory possibilities and how some of the overextensions students use can be the subject of fruitful engagement through negotiation based around representational modes.

Our study suggests various pedagogical benefits in focusing explicitly on representational issues to understand and promote students' conceptual learning. The study indicated how a focus on the students' attempts to represent their emerging understandings can provide teachers with strong evaluative insights into students' thinking, and can open up possibilities for teachers to probe students' ideas in a highly focused, generative way. The study also indicated that interactions with students around representations can also enable students to identify the adequacy of their representation for expressing their ideas, and allow the teacher to trace the emerging collective understandings of the class. The study also indicated that students need to develop an understanding of the signifying rules of their own representations, as well as those of more conventional science languages (verbal, mathematical and visual) if they are to engage effectively with learning how to interpret and represent science concepts.

We would argue, arising out of our experience in this study, for a science program that fore-grounded teacher-mediated negotiation of representational issues as students construct different modal accounts of a topic. Such a program would need to focus on student engagement with a range of their own, and more authorised accounts of the topic, supporting research by Russell and McGuigan (2001) on the need for re-representation work across different modes. Students also need explicit instruction in the signifying functions of various elements within different representations. For example, arrows in a diagram can variously indicate direction, force, or chronological sequence. In primary school, children need to start to learn and integrate the languages of science. This study implies the need for an increased focus on this dimension of meaning making in learning science, and provides new insights into student understanding and student learning in terms of representational knowledge and choices in developing meaning. Such a focus is embedded within a current Australian project, *Primary Connections* (Australian Academy of Science, 2005), which is developing science learning sequences with a strong literacy agenda.

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