Challenging the science curriculum paradigm: Teaching primary children atomic-molecular theory

Abstract

Solutions to global issues demand the involvement of scientists, yet concern exists about retention rates in science as students pass through school into University. Young children are curious about science, yet are considered incapable of grappling with abstract and microscopic concepts such as atoms, sub-atomic particles, molecules and DNA. School curricula for primary (elementary) aged children reflect this by their limitation to examining only *what* phenomena are without providing any explanatory frameworks for *how* or *why* they occur. This research challenges the assumption that atomic-molecular theory is too difficult for young children, examining new ways of introducing atomic theory to 9 year olds and seeks to verify their efficacy in producing genuine learning in the participants. Early results in three cases in different schools indicate these novel methods fostered further interest in science, allowed diverse children to engage and learn aspects of atomic theory, and satisfied the children's desire for intellectual challenge. Learning exceeded expectations as demonstrated in the post-interview findings. Learning was also remarkably robust, as demonstrated in two schools eight weeks after the intervention, and in one school, one year after their first exposure to ideas about atoms, elements and molecules.

Key words: Primary science learning, atomic structure, molecules, conceptual understanding

Introduction

Many countries, including Australia, are looking to science and scientists for solutions to contemporary issues. Australia's Chief Scientist has stressed the importance of investment in Science, Technology, Engineering, and Mathematics (STEM) to secure continued social, economic, and cultural prosperity (Australian Academy of Science, 2015, 2016; Chief Scientist, 2012, 2013). However, international measures such as PISA (OECD, 2016; Thomson, De Bortoli, & Buckley, 2013) and TIMSS (IEA International Study Center, 2016; Thomson, Wernert, O'Grady, & Rodrigues, 2016) have shown a decline in Australian students' performance relative to other countries, coincident with the decreasing participation in science in Australian education over several decades (AiAQ2ley, Kos, & Nicholas, 2008; Goodrum, Druhan, & Abbs, 2012; Lyons & Quinn, 2015). This has prompted international comment (Bagshaw & Smith, 2016) and responses from national policy makers (Chief Scientist, 2013) and science educators (Fensham, 2016; Marginson, Tytler, Freeman, & Roberts, 2013; Thomson, 2011; Treagust, Won, Petersen, & Wynne, 2015; Whannell & Tobias, 2015) championing the cause of improving science education, producing more highly qualified, respected and supported science teachers and in particular, increasing time spent on science in primary school.

A comprehensive literature review (Potvin & Hasni, 2014a) of research on students' interest, motivation and attitude to science documents that children aged 10 have positive attitudes towards science which declines sharply by age 14. This is consistent with Australian data extracted from TIMSS in 2011 showing that in Year 4, 55% of children like science which plummets to 25% of children in year 8 (Freeman, n.d., p. 20). Career aspirations are generally chosen by age 13-14 (Tytler & Osborne, 2012) and Year 8 students who expected to have a career in science are more likely to graduate with a science degree (Maltese & Tai, 2010; Tai, Liu, Maltese, & Fan, 2006). Furthermore, on pp. 22-23 of the *Securing Australia's Future* report (Freeman, n.d.), a study found that 'nothing' would influence Year 12 students' choice to study STEM post-school. Understanding and addressing factors impacting on primary students' interest and engagement in science is relevant as science graduates and/or scientists (Maltese & Tai, 2010; Venville, Rennie, Hanbury, & Longnecker, 2013) indicate that their interest in science was the most significant factor in pursuing a career in science, and was mostly developed before or during middle school. Curiosity, a desire to know how the world works, how and why things happen, were ideas commonly raised by respondents in Venville et al.'s (2013) study.

The failure of school science to retain students' interest in pursuing science in high school and beyond has led researchers to explore factors impacting on primary and middle school students' attitudes and aspirations towards science. A large number of variables have been identified which can be assigned to two broad groups; the first being school-related variables such as teaching quality and classroom experience, and the nature and relevance of the science curriculum to students' lives (George, 2006; Logan & Skamp, 2008; Lyons, 2006; Osborne & Collins, 2001; Osborne, Simon, & Collins, 2003; Potvin & Hasni, 2014a, 2014b; Tytler, 2009; Tytler & Osborne, 2012). The second group of variables are out-of-school influences such as gender (Archer et al., 2013; Archer, DeWitt, & Willis, 2014), ethnicity (Archer, DeWitt, & Osborne, 2015), socioeconomic status and home influences (Archer et al., 2012; Archer, DeWitt, & Wong, 2014), science capital (Archer, Dawson, DeWitt, Seakins, & Wong, 2015; DeWitt & Archer, 2015; DeWitt, Archer, & Mau, 2016) and parental attitudes towards science (DeWitt, Archer, & Osborne, 2013). In the Australian context, evidence from a recent study of regional Queensland parents' view of science education (Boon, 2012) shows that parents believed that what is taught in primary science has little relevance to their child's lives and that subjects such as geography, history or social studies gave children greater insight in socio-scientific issues. This view is disturbing in light of the current concern of policy makers, scientists and science educators about the need for more STEM graduates in the 21st century.

Literature review

This paper focuses on one particular in-school factor influencing children's interest and engagement with science, namely the nature of primary school science. The authors concur with the view that much of what is taught in primary classrooms bores children – they ask big questions and we give them little answers. Children are exposed to scientific, medical and technological advances in their everyday life through the use of technology and their exposure to the media and bring to school some knowledge of concepts such as the *big bang*, DNA and genes (Donovan & Venville, 2012). Yet the Australian science curriculum (Australian Curriculum, Assessment & Reporting Authority, [ACARA], (2017) leaves the big ideas of science such as atomic theory, DNA and natural selection until high school, when interest in science has declined. The authors suggest we may be leaving it too late to introduce children to the big ideas of science, the ideas that underpin scientific thinking, the ideas that explain how the world works and that satisfy curiosity.

The proposition that primary aged children should be introduced to the big ideas of science as explanatory tools to answer their *why* questions challenges the mandated content in the current Australian primary science curriculum (ACARA, 2017). The Australian curriculum introduces particles in Year 8 and atoms are not mentioned until Year 9, despite being part of two key concepts intended to be developed from Foundation year to Year 10. It is true that curricula in other countries are similarly conservative. In England, particles and atoms are introduced in the first year of high school (Year 7) (Department for Education, 2013), whilst in New Zealand, science is developed through the core strand of the nature of science, but the progression in chemistry introduces particles at Level 4 (Grades 7-9), elements and compounds at particle level at Level 5 (Grades 9-11), and distinguishes between atoms and molecules at Level 6 (Grades 10-12) (Ministry of Education, 2014). The US curriculum (National Research Council [NRC], 2012; Next Generation Science Standards [NGSS] Lead States, 2013) is more helpful and introduces particles and engineering ideas into elementary school. If interpreted and implemented as suggested, the US curriculum will give young children the opportunity to explore some of the *how* questions as well as the *what* questions about their world. However, it still leaves important theories such as atomic theory, to high school, limiting the capacity of children to answer the *why* questions that they might have.

Curriculum design has been driven by narrow interpretations of Piaget's (1936) theory of cognitive development, inferring that children cannot handle the big ideas of science until they develop abstract thinking at age 14. An Australian specialist science teacher has publicly challenged this thinking, contending that with appropriate pedagogy, young children *are* capable of grappling with the intricacies of atoms and molecules and are excited about learning about these microscopic components of matter. This research has sought to verify these claims.

As well as justified concern over future numbers of scientists, there is an expressed need for a scientifically literate citizenry. The continued presence of the dihydrogen monoxide meme from the 1990s (http://knowyourmeme.com/memes/dihydrogen-monoxide-hoax), where the majority of general public wanted to ban this substance, some going as far to petition their governments for a ban, indicates the dire need for greater literacy in chemistry as this compound is, of course, water. Scientific initiatives need to be for all. Another aim of this research was to show that with appropriate pedagogies, most, if not all children, could become empowered in science and more confident in their abilities. It was important that children enjoyed learning the science they learned. The specialist science teacher designed activities that are both hands on *and* minds on, and looked for signs that children enjoyed both the intellectual challenge of the activities and physically manipulating the models.

Children's conceptual thinking

The beliefs of Piaget and others that all children develop through the same stages at similar ages have been challenged on several fronts, which we will consider in turn.

Research in developmental psychology (Bidell & Fischer, 1992; Fischer & Bidell, 2006) finds that children's cognitive development shows variability in the age, synchronicity, and sequence of acquisition of specific skills, following multiple diverse pathways rather than a sequential ladder. Children's cognitive development is highly variable at all ages, in all areas of learning and at all points in learning. Variability exists within one individual (for example, between learning areas) as well as between individuals as Siegler has been saying for over a decade (Siegler, 1996, 1998, 2000, 2005, 2006, 2007).

From a science education perspective, Vosniadou and Skopeliti (Vosniadou, 2013; Vosniadou & Skopeliti, 2014) claim that conceptual change in science requires ontological, epistemological and representational changes in students' existing naïve conceptual structures. These changes are slow and involve fragmented ideas and the formation of synthetic conceptions as students attempt to reconcile scientific information with their prior conceptions. Students' conceptions and conceptual change and growth in science can be described as dynamic emergent structures which are non-linear processes requiring extended periods of time (Brown, 2014). A review of extant literature on cognitive and developmental psychology by Duschl, Schweingruber, and Shouse (2007) found that what young children are capable of learning is largely dependent upon their prior opportunities to learn rather than some fixed sequence of developmental stages. Lack of understanding of an individual or even a whole class does not mean that the material is developmentally inappropriate; it has more to do with a lack of prerequisite knowledge or an ineffective way of presenting the material (p. 150). This fits with Willingham's statement (2008) that

> For children and adults, understanding of any new concept is inevitably incomplete. . . . If you wait until you are certain that the children will understand every nuance of a lesson, you will likely wait too long to present it. If they understand every nuance, you're probably presenting content that they've already learned elsewhere. (p. 39)

Where might children have already learned science content prior to instruction? Fischer and Bidell (2006) extended their earlier work, and determined that the way people think is constructive, dynamic, and culturally embedded. If this is the case, then it follows that changing cultures can change the way people think. This second challenge to Piagetian ideas is based on the concept that the world has changed considerably since Piaget's time, with globalisation and access to modern media. Therefore, we are not challenging the validity of Piaget's findings for children of his time. However, we are challenging its continued validity for children in today's world where hyper-mediated children have more background knowledge and thus exposure to science.

Unfortunately, there is a dearth of research into just what knowledge children obtain from the mass media. A recent study conducted by one of the authors and her colleague (Donovan & Venville, 2012; 2014) of 141 children aged 10-12 years in four non-metropolitan areas in three Australian states reported an average level of exposure to media of 5 hours and 10 minutes per day. Although the Australian study design cannot demonstrate causality, nonetheless, the evidence did indicate the likelihood that the participants' knowledge of genes and DNA (which, like atomic theory, is not taught in schools until children are aged 14 or 15) has been derived from their exposure to the mass media. The same genetics themes arose from the children, particularly DNA being used to solve crime and to resolve family relationships, as appeared prominently in the media examples they mentioned (Donovan & Venville, 2012; 2014). Television (TV) was the main contributor to this usage, averaging 800 hours per year. Children are thus exposed to considerable input of information. Furthermore, this exposure to scientific information had excited their interest in science. Donovan and Venville (2012; 2014) found that 27% of the interviewed subsample of 62 children, despite their youth (10-12 years old), had engaged in their own research into DNA and genes. Some had achieved substantial in-depth understandings; for example, one 11-year old, 'Willis', could describe in detail the process of obtaining tissue biopsy samples to test for cancer, even knowing that tissue must be frozen to be able to be sliced sufficiently thinly. Another Australian researcher (Jakab, 2013) found that most of her participants aged 8 years or older could state some everyday knowledge of molecules when first asked, and some 11 year olds had sophisticated knowledge, one expressing the aspiration to become a particle physicist. TV and the Internet were also not the only sources of information. In Jakab's (2013) study, 11-year-old 'John' was very knowledgeable about molecules because he loves fantasy and science fiction books. He knew about methane from the plotline of a book that he had read. Thus, the participants in these studies support Tytler & Osborne's (2012) findings that primary children are highly interested in science. Indeed, they will actively seek out information once their science appetite is whetted.

Educational challenges to Piaget's thinking have been made at both of his designated stages 1 and 2 of child development. For example, children up to 7 years old (Stage 1) have been found to be more than simplistic thinkers and are able to engage in quite sophisticated reasoning processes that are the foundations for scientific thinking (Fleer, 2009), and use elementary conceptions of substance when discussing the process of evaporation (Tytler & Peterson, 2000). Children in Stage 2, between 7 and 13 years old, have been found to express naïve ideas of the particulate nature and behaviour of matter (Nakhleh & Samarapungavan, 1999). Jakab (2013) and Donovan and Haeusler (2015), both found that children in this stage could articulate ideas about molecules, particularly when offered the use of molecular artefacts such as symbols, diagrams, models and a website with interactive models. Furthermore, Murphy (2012) supports Vygotsky's contention that learning leads development, so teachers should always be challenging students rather than waiting for them to reach a predetermined developmental stage. Unfortunately, curricula do not always reflect these insights, and rarely give children the opportunity to engage with concepts beyond their current level of thinking or to revisit them periodically. Yet a longitudinal study of students in Grades 9 and 10 (Margel, Eylon, & Scherz, 2008) suggests that long-term development of the particulate model requires building a strong foundation of knowledge about the microscopic structure of materials through a process of spiral instruction. They acknowledge that despite the considerable time spent on instruction, existing traditional science curricula do not lead to robust particulate conceptions by the end of high school. Wiser & Smith (2008) further observe

> … science curricula treat knowledge as unproblematic facts; few students have any appreciation of the coherent nature of scientific theories or the role of ideas, models, and symbolisation, and cycles of hypothesis testing in their creation. (p. 226)

Johnson & Papageorgiou (2010) suggest that students' poor understanding of the particle theory of matter is a result of the 'solid, liquids, gases' context in which it is taught. Their work found that 9-10 year old children demonstrated greater understanding of the particle model when it was taught within the framework of a concept of substance. In the Australian Curriculum: Science (ACARA, 2017) students are taught to distinguish solids and liquids by appearance only in Year 3 without any explanatory mechanism such as the particle theory or atomic theory. It seems probable that children could develop the misconception that ice and water (a common example used) are two different substances, and the introduction of the abstract concept of heat causing change of state, also without an explanatory mechanism, is unlikely to help. Students' misunderstandings have been found to persist into senior high school and tertiary studies of chemistry (Özmen, 2004; Özmen & Alipasa, 2003; Stein, Larrabee, & Barman, 2008; Vosniadou, 2012).

Finally, neuroscience studies also indicate that the brain is more plastic than previously thought, with the first three years of life given over to the formation of new synapses between neurons (Gopnik, Meltzoff, & Kuhl, 1999). They showed that from a maximum of 15,000 synapses per neuron at age 3, adults have about half that number, so learning and development must involve a process of synaptic pruning and strengthening of some neural pathways at the expense of others. Sousa (2001) defined learning as the ability to acquire new knowledge or skills through instruction or experience, memory as the process by which that knowledge is retained over time, and plasticity as the capacity of the brain to change with learning. Recent neuroscience research suggests that ages 5-10 are years of heightened brain plasticity (Abdeldayem, 2012), which supports the idea that children may be particularly receptive to the foundations of scientific thinking during this time.

Other researchers have worked on ways of teaching advanced science to younger children, but to present time, curriculum policy has maintained distant from the outputs of such research. In 2004, Halpine exposed Grade 3 students to a one-hour digital presentation of molecular models, resulting in their ability to draw and describe accurate representations. In 2007, Acher, Arcà, and Sanmarti described how 7-8 year old children used a "model of imaginary parts" (p. 401) built from their ideas about discrete materials to explain the behaviour of different materials. Brown, Rushton, and Bencomo (2008) used ball and stick models to assist Grade 5 students to learn about important molecules and their properties. In 2009, Schwarz et al. found that the use of scientific modeling and argumentation in instructions is important in developing primary aged children's understanding of the atomic nature of matter.

Research focus

Support for working specifically with Year 4 Australian children (average age 9 years) in this study came from results from the Trends in International Mathematics and Science Study (TIMSS) in 2007. Australian Year 4 children achieved above average overall, and shared positive attitudes towards science with the average for the 36 participating countries (Thomson, Wernert, Underwood, & Nicholas, 2008). Yet both attitudes and achievement were much lower in Australian Year 8 children, with interest well below average. This raises the question: What happens between Years 4 and 8 to cause this decline? What science are children learning during this time and could this influence this trend?

The Australian Curriculum: Science (ACARA, 2017) for Years 4 to 8 deals with *what* questions. Chemistry deals with solids, liquids, and gases as separate entities, physical properties of materials, promotes the myth that physical changes are all reversible and chemical changes are all irreversible, what mixtures are, and how to separate them. No attempt is made to explain *why* these phenomena occur. The particle theory, offering some explanatory framework, is not introduced until Year 8. Could it be that the decline seen in TIMSS is at least in part due to children, full of curiosity to find out the *why* becoming bored with repeated exposure to the *what*? This research sought to shed light on this possibility.

Research questions

1. What attitudes to science do children aged 9 years hold and what do they perceive science to be?
2. What prior knowledge about atoms, molecules, and sub-atomic particles do children aged 9 years possess?
3. What knowledge about atoms, molecules, and sub-atomic particles can children aged 9 years gain through an intervention designed by a specialist high school science teacher?

Methodology

Participants

The study involved a retired high school chemistry teacher, who had gained significant local and national media interest for his claims that he could successfully teach atomic-molecular theory to Year 3 and 4 children and further, that they loved learning about atoms and molecules.

Our research involved children from three different primary Catholic primary schools, all located in Brisbane, Australia. The specialist teacher was new to two of the schools, but had taught children from the third school about atoms and molecules in the previous year. School A's intervention involved 26 Grade 4 children (and one Grade 1 child present by parental request) in an inner urban school. This was a diverse class with seven children with diagnosed special needs, including ESL (English as a Second Language), intellectual impairment, hearing impairment, and Autism Spectrum Disorder (ASD). School B was located in an outer suburb, with a random selection of 24 Grade 4 children from three separate classes in which the same specialist science teacher conducted the same intervention that was conducted in School A. Only one child in this cohort had identified learning needs. The intervention in School C, also a suburban school, involved a Year 4 class of 24 children who had some introductory lessons on atoms and molecules with the specialist teacher in the previous year.

Research Design

The research was conducted in four phases: the Pre-interview, the teaching intervention, the Post-interview and the Retention-interview. The Pre-interview was conducted by the authors in the week before the teaching intervention, the Post-interview in the week following the intervention and the Retention-interview approximately eight weeks later. The data were collected using semi-structured interviews (Creswell, 2005) allowing the researchers to rephrase questions and probe for understandings. Interviews were recorded and interview sheets completed at the time to record visual cues such as facial expressions and to aid the negotiation of meaning between interviewer and participant. In the interviews, children could respond orally, by drawing, and by manipulating models.

Informed consent for all cases was obtained from parents and children, and the research subjected to ethical scrutiny by Human Ethics committees from our University and the Catholic Education Office. Appropriate aliases were assigned to the children for use in publication and dissemination of results.

Pre-interview

The interviews were carried out by the authors in separate rooms and not in the classroom. Each child, in turn, was withdrawn from the classroom and interviewed individually. Before commencing the interview, children were assured that any information they would give would not reveal their identity and further, they were not obliged to answer questions and were free to discontinue the interview at any stage.

The set of questions put to the children relevant to the three research questions were:

a) Perception of and attitude to science

> What do you think science is?
>
> Do you like or dislike science? Why/why not?

b) Knowledge of atoms

> Have you heard the word atom?
>
> (If yes) What is an atom? What can you tell me about atoms?
>
> How big are atoms?
>
> Can you draw an atom for me? Explain what you have drawn.

c) Knowledge of molecules

> Have you heard the word molecule?
>
> (If yes) What is a molecule? What can you tell me about molecules?
>
> How big are molecules compared to atoms – bigger, the same size or smaller?
>
> Can you draw a molecule for me? Explain what you have drawn.

These questions were open-ended and asked in the listed order. Children were encouraged to explain further, including labelling of drawings; however, the interviewers gave no leading prompts or suggestions about what was expected in the responses, except to ask for further clarification of a response.

The intervention

The specialist science teacher, who was not involved in the research, conducted the intervention of about 10 hours of instruction at approximately 1 hour per week in Schools A and B. Because of unforeseen circumstances in School C, the intervention in this school was curtailed to 5 weeks and only involved a brief revision of atoms and molecules.

The intervention did not follow the usual method of introducing the particulate nature of matter through the context of the states of matter; rather, the teacher introduced children to atoms with reference to the elements of the Periodic Table. He demonstrated the relative size of atoms by allowing children to both heft and weigh samples of different metals and non-metals containing approximately equal number of particles and to place them in order on the Periodic Table. Elements were presented as unique substances made of one type of atom, and children made first-hand observations of the differences in appearance and electrical conductivity of samples of metals and non-metals. The concept of electrical charge was introduced through hands-on activities demonstrating attracting and repulsion, allowing an introduction to the charge, relative size and locations of protons, neutrons and electrons in atoms. Children were able to build the nuclear and electronic structure of the first 10 atoms of the Periodic Table, using a special *atom model* (built by the teacher in his home workshop) which is shown in Figure 1. Atomic number, earlier defined as the order of atoms/elements on the Periodic Table was now related to the number of protons and electrons in an atom (the number of neutrons was not emphasised). Simple properties of metals and non-metals were related to the electron-attracting power of the atoms (metals have loosely held electrons, non-metals have tightly held electrons). Simple molecules (H_2, O_2, N_2, H_2O, CO_2, and CH_4) were constructed by children using sets of molecular models and represented by them using molecular and structural formal notation. Valency was taught as the bonding capacity of atoms and explained using the octet rule. Children were encouraged to research given common molecular substances (e.g. sugar, acetic acid, glycerol, citric acid) and make models of these more complex molecules using learned valencies. Although the intervention involved short episodes of direct instruction, the teacher made regular use of discussion, analogies, models, bespoke videos, group work, hands-on activities and simple experiments. Children also completed work sheets and short quizzes. In the three schools, the science teacher was supported by the usual classroom teacher who assisted children with the group work, practical activities and worksheets. In School A, a teacher's aide was also present to give additional learning support to the special needs children.

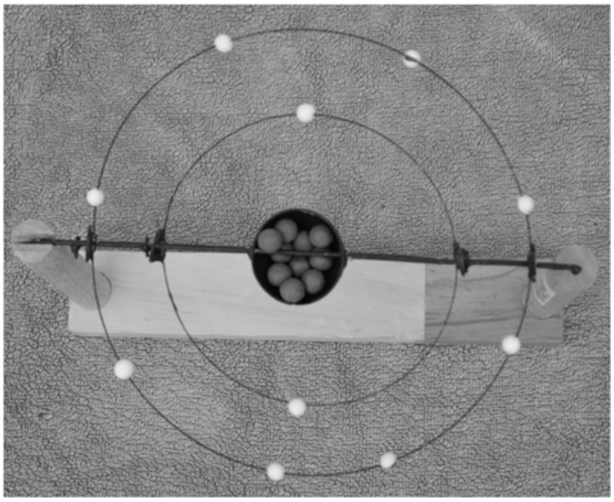


Fig.1 The *atom model* used to teach atomic structure

Post-interview and Retention-interview

These interviews were carried out in the same context as the Pre-interview and involved the same questions. Additional questions were also asked in these interviews, but this analysis focuses only on the questions in common across all three interviews.

Data sources and method of analysis

Primary data sources are the interviews subjected to conventional content analysis (Hsieh & Shannon, 2005) to produce scores and thematic analysis (Braun & Clarke, 2006) to reveal commonly held conceptions and misconceptions. Children's verbal responses and their drawing of atoms and molecules were analysed using the technique of analytic induction. This process involved continued readings of the children's responses by both researchers until agreement was reached on the common patterns that emerged.

The significance of observed differences between Pre-, Post- and Retention-interview results of the thematic analysis for each school was tested using the Wilcoxon signed rank test and for differences between schools for the same condition, the Mann-Whitney test was applied. Guttman scaling (Guttman, 1944) and McNemar tests were applied to data to determine ordered connections in children's understanding from atoms to molecules.

Secondary data sources for triangulation are the lesson reflections written by the specialist science teacher and children's responses to short quizzes administered in class.

Results and discussion

Perceptions of and attitudes to science

Content analysis of attitude to science

Content analysis (Table 1) revealed that almost all children brought a positive attitude to the intervention which was maintained following the intervention. Tom (School A) claimed "Science is to experiment and find out new things" before the intervention and after enthused "I like it a lot. Is fun. I find out things I didn't know- what atoms and molecules are". Only one child in each school believed science was "too hard." Two children in School B claimed that science was enjoyable when they were "doing experiments" but it was "boring listening to the teacher explain." Two complained "I don't like writing it up." These results are consistent with other research showing high positive attitudes towards science by 9 year-old children (Sorge, 2007; Thomson et al., 2016; Thomson et al., 2008).

Table 1: Pre- and Post-interview responses to "Do you like/dislike Science?'

Response	School A		School B		School C*	
	Pre	Post	Pre	Post	Pre	Post
"I love it"	0	1	1	2	4	3
Yes	23	23	18	19	19	19
Unsure/don't know	3	1	5	3	0	1
No	0	1	0	0	1	1
N	26	26	24	24	24	24

*Abbreviated intervention

It is interesting to note that in an Australian study of year 6 and 7 students (Logan & Skamp, 2008), 71% of year 6 and 100% of year 7 stated that they did not like writing and copying notes which is indicative of the transmissive pedagogical approach used in those children's classrooms. In contrast, only two of the 74 children in our study indicated that they did not like "writing up science." The teachers' lesson plans and reflections on classroom practice in Schools A, B and C revealed minimal teacher talk, lots of hands-on activities, no note copying and only a small amount of writing involved in completing data sheets for the activities or quizzes.

Thematic analysis of perceptions of and attitudes to science

Thematic analysis of the interview data identified 93 components represented in children's responses to the questions "What is science?" and "Why do you like science?" These components were classified by the researchers under 6 themes and 19 sub themes as shown in Table 2 and used as a framework for analysis. The results of this analysis for Pre- and Post–interview data for Schools A, B and C are shown in Table 3.

Four of these themes, *How the world works*, *Science content* , *Working scientifically*, and *Helping the world* align with the categories, *Study of the world*, *Body of knowledge*, *Process* and *Search for new* *developments* used by Murcia & Schibeci (1999) in research on preservice primary teachers' conceptions of the nature of science. A more recent study (Demir, 2015) of third grade elementary students' written responses to the question "What is Science?" identified seven dimensions, *Affective, Processes, Product, Scientific Field, Cognitive, Characteristics* and *Human.* The first four relate to our themes, *Affective, Working scientifically, Helping the world and Science content knowledge* whilst Demir's last three dimensions relate to our theme called *Learning.*

Table 2: Framework for analysis of children's responses to "What is science?" and "Why do you like/dislike science?"

Theme	Sub themes	Components
How the world works	About how the world works	how the world works, science is in everything
	A way of knowing how the world works	a way of describing everything on earth, discovering how the world works, finding new things, a way to find out answers
Science content knowledge	Physics	gravity, pushes and pulls, friction, rockets, temperature, light, magnets
	Chemistry	chemistry, chemicals, atoms, molecules, atomic number, symbols, electrons, bonds, protons, elements, helium, hydrogen, formula, H_2O, nucleus, Periodic Table, air, solids, liquids, gases, compounds, explosions
	Earth Science	geology, earth composition, rocks, volcanoes, fossils, dinosaurs, the atmosphere
	Space	space, Mars, galaxies, the Sun
	Biology	nature, animals, plants
Working scientifically	Science methodology	research, experiments, testing, mixing, results, data, measuring, predicting, comparing,
	Collaboration	working with others
Helping the world	Community and environment	making the world a better place, helping the environment, help people in the future
	Medicine	curing diseases/cancer, medicine
	Technology	creating/making new things, inventions, technology, touch screens, phones
	Using science	recycling, cooking/food, use in sport
Learning	Learning about science in school	learning in school, a school subject
	Learning science out of school	learning out of school (parents, books, media, outdoors)
	Learning for a purpose	learning for the future, a career, high school
	Science Learning process	learning through/by using your brain, challenging me, class activities, school projects
Affective	Affective positive	fun, interesting, rewarding (I can understand it), favourite subject, like the teacher
	Affective negative	too hard, conflicts with religion

Analysis of children's responses to "What is science?"

The results of applying the analytic framework to Pre- and Post- interview responses from Schools A, B and C to the question "What is science?" are shown in Table 3.

Table 3: Pre-and Post-interview responses to "What is science?" (percent of the class)

	School A N=26		**School B N=24**		**School C N= 24**		**All Schools N=74**	
Themes	Pre	Post	Pre	Post	Pre	Post	Pre	Post
How the world works	31	25	38	42	33	46	34	35
Science content knowledge	54	33	71	46	42	33	55	36
Working scientifically	62	63	29	50	50	46	47	51
Helping the world	19	29	38	50	13	21	23	32
Learning	30	38	33	13	29	38	28	28
Affective	8	8	0	4	13	4	7	5
No response/don't know	8	4	0	4	4	4	4	2

*Total percent is greater than 100 as many children gave combined responses

In contrast to the views of adult preservice teachers (Murcia & Schibeci, 1999) where 63 % of the respondents articulated a broad view of the nature of science, just over one-third of Grade 4 children had a similar understanding, reflecting their more limited experience of science. About 50% of Grade 4 children referred to science being about experiments, with about one-third mentioning particular science content (e.g. chemicals, magnets, animals, space) or practical applications that helped the world (e.g. technology, medicine). Science was seen as an educational experience (e.g. learning about science) by 28% of the children overall.

Further interrogation of the data showed that over 70% or children's responses fell into two or more worldviews. A range of typical responses are shown.

Seb (School A) had a **broad view** of science including science content knowledge and processes, and its educational role.

Pre-interview: "Science teaches us about galaxies and the Sun. It's about experiments and how the world works."

Post-interview: "Science is about questions and answers that people may not know about the world, like atoms, elements and molecules."

Loughlin (School A) had a **utilitarian view** of science,

Pre- interview: "Science makes the world a better place. It's about chemicals."

Post-interview: "Science helps people and makes the world a better place. It's about litter and helping animals survive."

India (School B) had a mostly **process view** before instruction which expanded to a **broader view** following the intervention.
Pre-interview: "It's technical things like measuring, growing, experiments and testing things."
Post-interview: "It's using different types of liquids in complicated experiments where you are testing out things. How things work."

Ian (School C) had a science **content knowledge view**.
Pre-interview: "Science is about space, atoms, molecules, minerals."
Post-interview: "Science is about everything …molecules, atoms, space."

Also interesting was the relative frequencies of disciplines evident in the responses. Chemistry content was mentioned with far greater frequency than all of the other discipline areas. There were 29 references to chemistry terms such as chemicals (9) and atoms (6), molecules (7) at the Pre-interview which was over twice the number of each of the other disciplines – Physics (6), Space (9), Earth (13) and Biology (12). References to Chemistry content increased to 76 at the Post-interview compared to 16 for all other disciplines combined and included high frequency words such as atoms (32), molecules (14), elements(5) and the Periodic Table (5). Reflecting what was fresh in the children's minds at the Post-interview could explain those results, but this does not explain the prevalence of Chemistry in the Pre-interview, when they had been studying other topics.

Analysis of children's responses to "Why do you like/dislike science?"
Applying the analytical framework to children's reasons for liking or disliking science revealed two striking observations: children's very positive affective view of science and an expressed love of learning about science in general or particular aspects of science (Table 4). There were high frequencies of statements that science was fun/interesting because of the experiments, nature of the science content or learning how the world works. Following the intervention, children commonly mentioned that they liked learning about aspects of atomic theory. In School C, where children had lessons on atoms and molecules in the previous year, many of them recalled this and included it in their reasons for liking science.

Table 4: Pre-and Post-interview responses to "Why do you like/dislike science?" (percent of the class*).

Theme	School A N=26		School B N=24		School C N= 24		All Schools N=74	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
How the world works	15	8	8	25	25	25	16	11
Science content	46	42	42	46	38	25	42	28
Working scientifically	19	54	17	21	46	33	27	24
Helping the world	15	8	13	4	4	13	11	4
Learning	31	33	46	50	38	46	38	26
Affective	65	63	54	42	42	33	54	34
No response/don't know	15	4	0	8	4	17	7	5

*Total percent is greater than 100 as many children gave combined responses

Some examples of the types of responses are:

School A

Tom found science fun, liked collaborating to find answers and learning about atoms and molecules. He expressed a **collaborative discovery view** of science.

Pre interview: "It's fun experimenting. I like to work with partners to find out stuff you don't know."

Post-interview: "I like science a lot… it's fun, I find out things I didn't know, what atoms and molecules are."

Nathan liked gaining knowledge and understanding. He expressed a **cognitive view** of science.

Pre-interview: "It's fun. You know things like cure for cancer, bones."

Post-interview: "I get the theories… understand electrons….I can write formula… the chemical formula such as CH_4."

Emilia enjoyed atoms and molecules after learning about them. She expressed a **process vie**w of science.

Pre-interview: "It's fun mixing chemicals. I saw this (on TV)."

Post-interview: "Science is building atoms, worksheets, finding elements & atomic numbers, letters."

School B

Olivia wanted to know more and believes science is something you would follow up out of school. She expressed an **inquiring view** of science.

Pre-interview: "I want to know more. I don't know much. Science might be interesting".

Post-interview: "Science is something I can do in my spare time. It's interesting. What is true/false - facts about space."

Sonja loved learning new things, including atoms. She articulated the **tentative nature** of science.

Pre-interview: “I love it. It’s fun…new things to learn.”
Post-interview: “I really enjoy science. You can get answers you don’t already know.”
Post-interview: “It all makes sense. There is usually more than one answer. I like doing experiments.”

School C
Alexander liked learning science, expressing a **cognitive view**.
Pre-interview: “I like to like to find lots about animals… and like speed ... inventions. I like reading big books about science. I think science is really fun.”
Post-interview: “I like learning about atoms and protons and electrons.”

Jamey liked the surprise of learning something unexpected, articulating a **discovery view** of science.
Pre-interview: “Lots of stuff that is unexpected. Lots of interesting facts.”
Post-interview: “It’s very fun and you don’t know what’s around the next corner.”

Lucien liked learning about atoms and molecules. Lucien combined **discovery and cognitive views** of science.
Pre-interview: “I like science because you get to discover new things and you get to learn about different types of molecules.”
Post-interview: “I like learning about different kinds of atoms and molecules and elements.”

As noted previously, only two children stated that they disliked science because it was “too hard” or “I’m not good at it.”

It is interesting to compare what children liked about science with what they believed science to be. Our results reveal that children expressed enjoyment in learning about science, and specifically about atoms and molecules and/ or doing experiments in the classroom. This favourable attitude to learning atomic theory contrasts with the perceptions that older children have about the physical sciences. Physics and chemistry are not very popular with 14 year old high school students (Tytler & Osborne, 2012, p. 604), yet here, year 4 children were excited by atomic theory, one of the big ideas of the physical sciences. A literature review (Potvin & Hasni, 2014a) found that science is perceived to be increasingly difficult from Years 5-11 which contrasts with our results where only 2 out of 74 children expressed concern about the difficulty of science and learning about atomic theory. The significant difference between primary students and high school students’ perceptions and attitudes towards science begs two questions. “Why do 9 year children enjoy learning about atoms and molecules, usually taught at high school, and do not find it too difficult?” and “Why do older children find science increasingly difficult and show decreasing interest in chemistry and physics?”

In conclusion, our results show that primary school is fertile ground for developing children's love of and interest in science. Noteworthy is their curiosity in wanting to know how the world works, and believing science is about this. Children believe science is about doing experiments and these made science enjoyable. Most liked or loved science because "It's fun" or "interesting" and satisfies their curiosity. Importantly, many children said they liked learning about atoms and molecules because it allowed them into a world that they didn't know existed and this was viewed with wonderment. As Kevin (School B) and Nathan (School A) stated, respectively, "I like science because you discover new things no-one see before" and "I get the theories, understand electrons, I can write chemical formula such as CH_4."

Children's knowledge of atoms and molecules

Content analysis of children's knowledge of atoms and molecules

Children in Grade 4 bring to the teaching intervention varying amounts of prior knowledge of the terms atoms and molecules (Table 5). Children in School C had lessons on atoms and molecules with the specialist science teacher the year before, whilst those in Schools A and B had no previous formal instruction. The few children in Schools A and B with prior knowledge claimed they had gained this knowledge from books; the internet; TV (such as *Mythbusters*, *Big Bang Theory*); parents, siblings or other adults; teachers, scientists or science at school; or family visits to science centres or museums. In School C, one child new to the school claimed he learned about molecules at his previous school. All of the other children in School C said they knew about atoms or molecules from the previous year's instruction in Year 3.

Table 5: Pre- and Post-interview responses to "Have you heard the word atom/molecule?"

	Have you heard of the word *Atom*?						Have you heard of the word *Molecules*?					
	School A		School B		School C		School A		School B		School C	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Yes	3	26	7	24	24	24	13	24	14	24	22	24
No	23	0	17	0	0	0	13	2	10	0	2	0
Total	26	26	24	24	24	24	26	26	24	24	24	24

The results from School C indicate that familiarity with the words *atoms* and *molecules* is persistent; these children remembered them over the course of a year. This suggests that teaching such ideas in primary school results in worthwhile learning. Results from Schools A and B indicate that the word *molecule* is encountered more frequently in everyday life than is the word *atom*. It would be interesting to follow up why this might be, where children are encountering *molecules*. Children in both Schools A and B also demonstrated gratifying familiarity with these words after the intervention.

Thematic analysis of children's verbal responses and their drawings of atoms and molecules

The use of students' drawings has been used as a research tool to identify their ideas and misconceptions (Adbo & Taber, 2009; Cokelez, 2012; Cokelez & Dumon, 2005; Kiray, 2016; Köse, 2008). We propose that children's drawings represent their mental models of atoms and molecules and give some insight into their level of knowledge and of understanding these entities (Park & Light, 2009; Vosniadou, 2002).

Thematic analysis of children's drawings of atoms and molecules revealed a wide range of drawings which fell into three broad categories representing different amounts of information about atoms or molecules. The most detailed group of drawings represented atoms and molecules with an internal structure composed of smaller particles. The next category represented atoms and molecules as simple particles with no internal structure and the last category contained drawings that represented atoms or molecules as macroscopic objects. Non responses were also included in this category. These three categories of drawings for atoms and molecules represent different levels of children's understanding about these entities and are shown in Table 6, together with definitions and descriptions of the types of drawings contributing to each level.

Table 6: Framework for analysis of children's drawings of atoms and molecules

Level	Category	Definition	Description of types of drawings
A2	Atoms are MADE of smaller particles	Atoms are drawn to show an internal structure and/ or component particles	Bohr models showing evidence of location and/or charges of electrons/ protons/neutrons Solar system/concentric circles/ showing some component particles
A1	Atoms ARE particles	Atoms are drawn as particles with no internal structure	Small individual spheres, circles or dots Groups of joined spheres or drawn as molecules
A0	No understanding	Macroscopic entity or no response	Germs, large blobs
M2	Molecules are MADE of atoms	Molecules are drawn showing particles joined together	Specific molecules (ball and stick, structural or molecular formula) Particles joined or bonded together
M1	Molecules ARE particles	Molecules are drawn as particles with no internal structure	Molecules drawn as atoms Non-identified particles
M0	No understanding	Macroscopic entity or no response	Germs, large blobs

Thematic analysis of only the children's verbal responses to the questions about the nature and size of atoms and molecules provided less information about their thinking than their drawings. Some of the children had difficulty verbally articulating what an atom or molecule looked like and found it easier to draw and label their drawings. In applying the Framework we chose to apply it first to children's drawings and then refer to their verbal responses about atoms and molecules to moderate coding decisions.

Analysing children's drawings and statements about atoms prior to and after the teaching intervention

About 90% of children from Schools A (24/26) and B 20/24) brought no prior understanding of atoms or molecules to the teaching intervention (Table 7). Only one child demonstrated any prior knowledge of the sub-atomic character of atoms and that molecules were made of atoms. In contrast, a majority of children from School C retained knowledge of atoms as particles (22/24) and molecules (62%) from their lessons in the previous year. These data suggest that without specific teaching, most 8-9 year old children have not yet developed an intuitive theory about the particulate nature of matter.

Table 7: Classification of Pre-, Post- and Retention-(Ret) interview responses of Year 4 children's drawing and answers to questions about atoms

Level	**Category**	**Grade 4(A)**			**Grade 4 (B)**			**Grade 4(C)**	
		Pre	Post	Ret	Pre	Post	Ret	Pre	Post
A2	Atoms are MADE of smaller particles	1	13	9	0	15	13	2	4
A1	Atoms ARE particles	1	12	15	4	9	9	17	19
A0	No understanding	24	1	2	20	0	2	5	1
	Total	**26**	**26**	**26**	**24**	**24**	**24**	**24**	**24**

Following the teaching intervention, significant gains in understanding were made by the children in Schools A and B (Wilcoxon signed-rank, $p<.05$). As expected, the understanding of a few (but not statistically significant ($p>.05$)) children was not consolidated. Four from School A and two from School B who identified the sub-atomic structure of atoms in the post-interviews failed to do so eight weeks later. Nonetheless, one third of the class in School A (9/26) and just over 50% of the class in School B (13/24) were still able to describe details of an atom's composition after this period. Further, the differences in levels of understanding between the children from School A and School B are consistent with the different nature of the cohorts. Seven children in School A had identified learning difficulties compared to one child in School B.

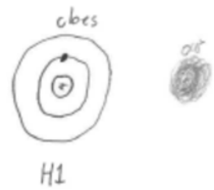
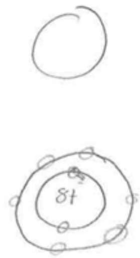
Retention data was not collected from School C because of the limited intervention. However, it is clear that after their instruction in the previous year, these children retained the understanding that matter is particulate.

Children's mental models of atom structure after the teaching intervention

Children's drawings, together with their verbal responses to the sequence of questions about atoms provide some insight into children's development of conceptual understanding about atoms. Within the A2 category (Atoms are made of smaller particles) we included a range of children's responses, from those which accurately represented the structure of atoms in Bohr diagrams to those that had incomplete or fragmented understanding of atomic structure.

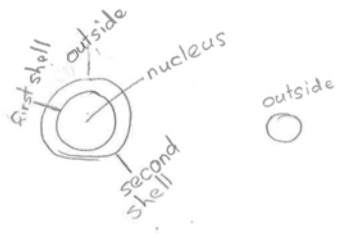
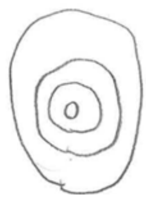
At the Post-interview, 27% (7/24) from School A, 42% (10/24) from School B, and 8.5 % (2/24) from School C were able to describe and/or accurate draw Bohr representation of actual atoms, showing the correct number, location and charge of electrons and protons in actual atoms. Table 8 shows some examples of these responses. Andrew (School A) and Jackie (School B) had no understanding of atoms prior to the teaching intervention, but after instruction were able to correctly represent the nuclear composition and electronic structure in Bohr drawings of atoms of their own choosing. Ilsa from School C, remembered from instruction a year earlier that atoms were very small particles that made up everything, but had forgotten about electrons and protons. After the intervention she represented boron atom with its sub-atomic structure.

Table 8: Post-interview Bohr diagrams with correct atomic structure of atoms

Analysis of children's drawings and verbal responses about atoms	Post-interview drawing
Andrew (School A) had no prior knowledge of atoms. After the intervention he said that "Everything is made of trillions and trillions of atoms and they are very small and about a picometre." His drawings represented two views of the H atom - at a distance the H atom looked like a round cloud but "cloes "(sic) up, the positive proton and the one electron in the first shell could be seen.	
Jackie (School B) had no prior knowledge of atoms. At the Post-interview she said "atoms were a kind of tiny particle that make up everything and they cling together to make molecules." She represented an oxygen atom in two ways - as a simple particle (the circle) and an interval view of the oxygen atom with 8+ protons in the centre and 2 electrons in the 1st shell and 6 in 2nd shell.	
Ilsa (School C) remembered from earlier learning that "atoms made up everything, were very tiny and can't be seen." "They make up different things and there were lots of them". She represented atoms as lots of small circles. At the Post-interview she stated that "atoms made up solids, liquids and gases and groups (molecules"). She first drew an atom as a circle/sphere and on reflection redrew a boron atom.	

Another 23% (6/26) from School A, 21% (5/24) from School B and 8.5% (2/24) from School C drew and described atoms as having components which were not clearly defined. Table 9 shows four typical examples. Connie had a good understanding of atomic structure in general terms but did not give an example of a specific atom. Harry explained that electrons were located on the shells and protons were in the middle but his drawing did not show these clearly. Jamey from School C remembered from prior learning that atoms had “electrical” components located within atoms. Following instruction a year later, his mental model of an atom changed to concentric circles with a nucleus inside, although he did not show the actual position of the nucleus. Emilia (School A) knew that atoms had constituents but did not give the particle names or explain how her statements about the lithium atom related to her drawing of dots in a circle.

Table 9: Post-interview variations of Bohr diagrams showing incomplete atomic structure

Analysis of children’s drawings and verbal responses about atoms	Drawing
Connie (School B) had no prior knowledge of atoms. After instruction she said that atoms were “10 billionth of a metre or something like that” and “They make up everything”. Her drawing of the atom showed two perspectives, an external view of a small circle and an inside view showing a generic structure of a nucleus and electron shells.	
Harry (School A) had no prior knowledge of atoms. After the intervention he said that atoms are “Really small, smaller than an ant and make up things like wood and paper”. His drawing showed a central particle surrounded by concentric circles. He explained the drawing by saying that “protons go in the middle and electrons go in the shells.”	
Jamey (School C) remembered atoms from lessons a year earlier. “Everything is made of out of atoms. There are different formulas to make different atoms. Atoms are really small - about a million or more in each thing.” He explained his Pre-interview drawing of small circles within a larger circle as “The outer circle is the atoms and the little things inside are electrical”. At the Post-interview he said that an atom is “A little thing that everything is made out of. They are really very small and a million fit into a very small space”. He explained that concentric circles in his drawing had a nucleus inside.	 Pre-test  Post test
Emilia (School A) had no prior knowledge of atoms. After instruction, she responded: “Elements are made up of one type of atom. We are made up of different atoms, atoms make up everything. Atoms are very small and you can’t see them”. Her naïve drawing showed particles inside a circle	

Drawings of atoms as circles or spheres and without an internal structure which were supported by verbal responses describing atoms as very small particles that made up everything were assigned to the A1 category – Atoms are particles. Only one child in this group stated that atoms were made up of protons and electrons but was unable to represent them in a drawing. Only a few children stated atoms were "in" things or called atoms "molecules".

These results are remarkable since no indication was given by the interviewers about what was expected in the drawings. The only prompts given were requests to explain further or label diagrams.

Overall, the children in School B demonstrated greater understanding than children in Schools A and C. This result is consistent with the differences between the schools and the nature of the intervention. The School A cohort comprised 7 children (27%) with a range of learning difficulties, including intellectual impairment, speech language difficulties, and hearing impairment whilst School B had no children with challenging learning difficulties. In School C, the teacher's written and verbal reflections of the lessons showed that because of the lack of time, the children were unable to engage with the atom model activities, whereas in Schools A and B, a number of lessons were allocated to hands-on modelling using the atom model. It would appear that the use of the atom model allowed over 50% of children in Schools A and B to integrate information about the structure of atoms into their mental picture of atoms, whilst the absence of modelling in School C resulted in more fragmented understanding of atomic structure.

Overall, our results suggest that almost all 9 year old children participating in the research study are able to grasp the concept that matter is particulate if it is explicitly taught ,with a smaller but not insignificant percentage being able to represent fundamental aspects of sub-atomic structure in response to open-ended questioning that allowed them to respond as they wished.

Analysing children's drawings and statements about molecules prior to and after the teaching intervention

Analysis of children's drawings of molecules using the classification framework of Table 6 and moderated by their verbal responses is shown in Table 10. At the Pre-interview about half of the children in Schools A and B claimed to have heard the word molecules (Table 5) but only 5 were able to define or draw a molecule (Table 10). In contrast, all but 2 of the children in School C recognised the term from earlier learning and over half were able to represent molecules in some way.

Table 10: Classification of Pre, Post and Retention (Ret) interview responses of Grade 4 children's drawing and answers to questions about molecules

Level	Category	Grade 4(A)			Grade 4 (B) N=24			Grade 4(C) N=24	
		Pre	Post	Ret	Pre	Post	Ret	Pre	Post
M2	Molecules are MADE of atoms	1	14	16	0	19	18	9	19
M1	Molecules ARE particles	2	4	4	2	5	3	5	4
M0	No understanding	23	8	6	22	0	3	10	1
	Number	**26**	**26**	**26**	**24**	**24**	**24**	**24**	**24**

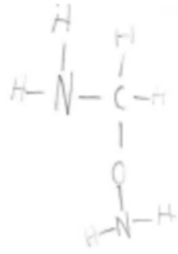
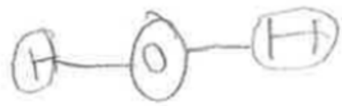
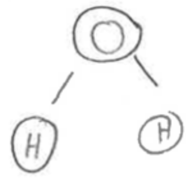
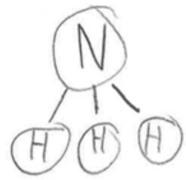
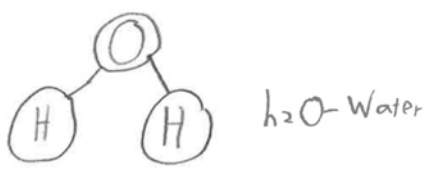
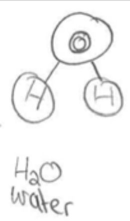
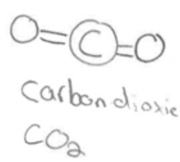
Following the teaching intervention, significant gains in understanding were made by the children in all schools (Wilcoxon signed-rank, $p<.05$). The small loss in understanding at the Retention-interview by School A and B was not significant ($p>.05$).

Understanding molecules depends on atoms as pre-requisite knowledge, but despite this extra conceptual complexity for molecules, over half (14/26) of the School A class at the Post-interview knew that molecules were composed of atoms and could draw representations of molecules. It is interesting to note that this number increased to 16/26 eight weeks later. We have no clear explanation of why this happened except to suggest that the Post-interviews may have prompted two children to clarify their understanding. Children in School B and School C demonstrated a greater overall understanding that molecules were made of atoms in the Post-interviews (19/24) with a small reduction in School B after 8 weeks. In School C, 9/24 children retained knowledge of molecules from the previous year which increased to 19/24 after the limited intervention. This result for School C supports the notion that revisiting concepts the following year assists children in building and retaining understanding.

Children's mental models of molecules after the teaching intervention

Table 11 shows samples of children's drawings of correctly represented molecules, together with their verbal responses. The samples were chosen from Schools A and B where Post- and Retention- data was available. All of these children knew that molecules were bigger than atoms. The authors acknowledge that a small molecule such as H_2 is smaller than a large atom such as uranium, but the thrust of the teaching intervention was to explain molecules as groups of atoms and thus larger than their component atoms. Their response and explanations all clearly demonstrate a correct understanding of the valencies of different atoms and how atoms combine to form molecules and the examples selected showed no loss of understanding at the retention-interview. The learning of these children is robust after eight weeks.

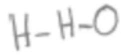
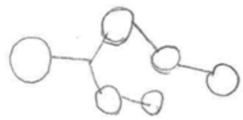
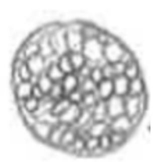
Table 11: Post-interview and retention-interview verbal responses to “What is a molecule?” and drawings of correctly represented molecules

Analysis of children’s drawings and verbal responses about molecules	Post-interview drawings
Seb (School A) drew correct structural formulae with correct valencies for his own made up molecule. *Post-interview:* “Atoms joined together. Molecules make up things like wood and H_2O which is water”.	
Retention-interview: “You breathe in oxygen and breathe out carbon dioxide”. Seb drew correct structural formula of two molecules.	 
Loughlin (School A) who is ascertained as ASD, showed considerable insight in his post drawing. *Post- interview:* “How atoms can join other atoms. Hydrogen can join oxygen as it has two spaces left and hydrogen has one. So two hydrogen can join it.”	
Retention-interview: “Molecules are atoms joined to other atoms”. Loughlin drew a ball and stick representation of water.	
Ted (School C) drew correct ball and stick representations of water and ammonia. *Post- interview*: “Molecules are atoms joined together.”	 
Retention-interview: “Molecules are made of atoms—two different ones joined.”	
Shelly (School B) drew correct ball and stick molecules and molecular formulae. *Post- interview*: “Molecules are the same or different atoms put together. Water has two types of atoms, also ammonia, methane, carbon dioxide. Oxygen has two bonds, and hydrogen has one bond.”	 

Retention-interview: "Molecules are made of more than one atom. Water is hydrogen and oxygen and there are other types."	

Drawings and responses from children who knew that molecules were made of atoms and thus bigger than atoms, but demonstrate partial understanding of how atoms were bonded are shown in Table 12. These drawings show typical misconceptions including incorrect understanding of valency and how atoms bond to form discrete entities.

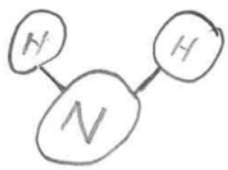
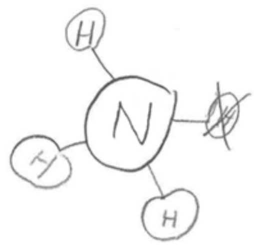
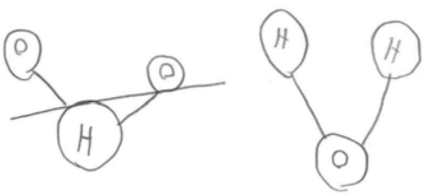
Table 12: Post-interview and verbal responses to "What is a molecule?" and drawings of molecules from Schools A and B

Analysis of children's drawings and verbal responses about molecules	Drawing
Olinda (School A). Her initial drawing revealed lack of understanding of valency, *Post- interview*: "Lots of atoms joined together with bonds." *Retention-interview:* "Molecules are different atoms joined together". After eight weeks Olinda's drawing showed she had forgotten specific atoms and valencies.	 
Monica (School B). Her drawings revealed her lack of understanding of bonding and valency. *Post- interview*: "Molecules are made up of atoms and electrons and protons. They are made of … hundreds? .. of atoms mixed up." *Retention-interview:* "Groups of atoms put together".	 

Analysing the effect of revisiting the intervention after 1 year

Children from School C were taught about atoms and molecules by the specialist science teacher when they were in Year 3, one year earlier. The Pre-interview data in Table 10 shows that 9/24 could explain and draw that molecules were made of atoms which is indicative of the extent of the retention of knowledge after 1 year. With limited revision, another 10 children were able to reclaim this understanding. Table 13 shows 2 samples of Pre- and Post-interview responses and drawings from School C. This result shows the necessity for revisiting and building on previous learning.

Table 13: Pre-interview and post-interview verbal responses to “What is a molecule?” and drawings of molecules from School C.

Analysis of children’s drawings and verbal responses about molecules	Drawing
Ian (School C) drew a ball and stick representation of ammonia but had forgotten the valency. *Pre- interview*: “A molecule is one or more atoms.”	
Post- interview: “A molecule is made of atoms and they are small like atoms”. He drew ammonia with 4 bonds, and then corrected it to show three N-H bonds.	
Katherine (School C) conflated atoms and molecules and was unable to explain the difference. She drew a circle to represent a molecule. *Pre-interview*: “Molecules are different types of things on the Periodic Table that go together to make new things. They are different to atoms.”	
Katherine (School C) still confused the nomenclature of atoms and molecules in her explanation. She first drew water as O_2H, realised it was wrong and redrew it correctly. *Post- interview*: “You put molecules together to make a new one. There are lots of different types.”	

In summary, the analysis presented here clearly demonstrates young children’s capacity to understand the atomic and molecular nature of matter and to retain this knowledge, even after a period of up to one year.

Building mental models of atoms and molecules

The results of a Guttman analysis of the Post-interview data of atoms and molecules are summarised in Table 14. Only two children who drew representations of molecules could not draw an atom, however, these children's verbal responses about atoms showed some knowledge of atoms - they both described atoms as very small components of the material world. It is possible these two students may have been able to draw an atom with more probing interview questions.

Table 14: Results of Guttman analysis of Post-interview data of atoms and molecules

	Molecules are MADE of atoms	Molecules are particles	No understanding of molecules
Atoms MADE of smaller particles	24	4	4
Atoms are particles	26	8	6
No understanding of atoms	2	0	0

McNemar tests on the data showed the following ordered connections: an understanding of atoms is a prerequisite for understanding molecules (p = .039); an understanding of atoms as particles is a prerequisite for understanding atomic structure (p = .000) and an understanding of molecules as particles is prerequisite for understanding molecular structure (p = .000).

Classroom test

Children's responses to the post interview questions were scored and compared to the grades awarded in the final in-class test covering similar content about atoms and molecules. These results, expressed as a percentage are shown in Figure 2 for School B.

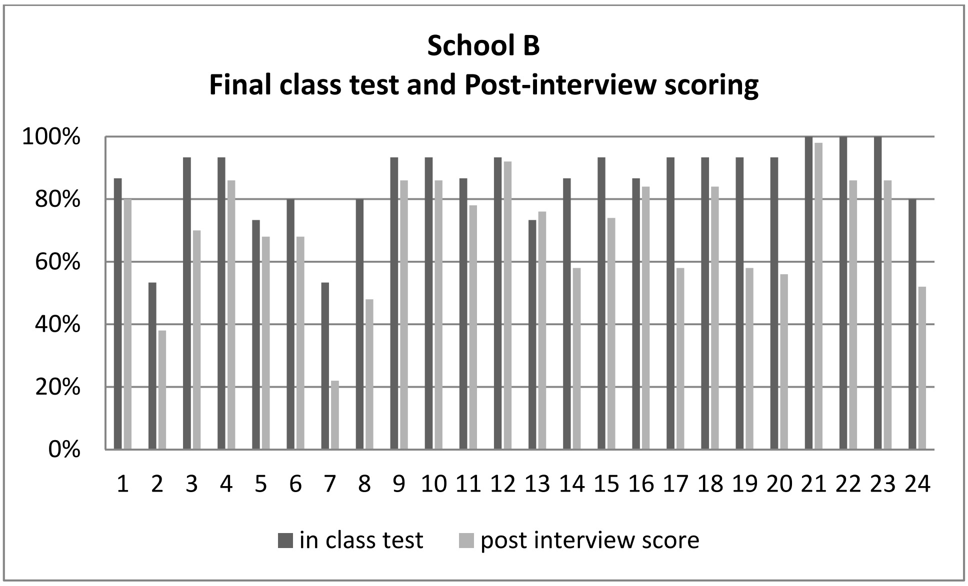


Fig.2 Final class test and post-interview scoring in School B

The graph in Figure 2 reveals that in most cases, the post interview scores were less than the in-class tests. The Post-interview afforded conditions that were more challenging: children were asked questions orally without visual or written prompts, whereas the test comprised some multiple choice items, true/false match, diagrams to label, and cloze items. However, as discussed, children's responses in the Post-interview revealed significant understanding of atoms and molecules.

Teacher reflections

The interview questions, designed before the intervention, were derived from an interview with the specialist science teacher who described the scope and sequence of teaching activities and presented copies of his formative assessment tests and teaching models. Our interview questions were similar to but not identical to the quiz items. Children's written responses to the classroom tests showed that most students were able to complete the quizzes successfully; however, it was not possible to ascertain the degree of assistance from peers or teacher aides. Inspection of the specialist teacher's reflection on his practice indicates that he regularly checked for understanding through questioning, observing individual and group work and marking formative class room work. On several occasions, feedback from the class caused him to revisit more difficult aspects. In School A, he used the attraction and repulsion of magnetic poles as an analogy to consolidate understanding about repulsion and attraction of opposite charges, but found children conflated electric charge and magnetic poles. Magnetism was not included in the interventions in Schools B and C. Similarly, he described units of length using powers of 10, which exceeded students' level of numeracy, so he omitted this from the later interventions. Apart from these minor changes, the content covered in Schools A and B was identical. In School C, the limited intervention revisited atoms, elements and molecules and only briefly reviewed atomic structure.

Limitations of the study

As this study is not an experimental study, generalisations cannot be made as it was not possible to control all possible factors influencing student learning in the intervention. Although the specialist teacher was not part of the research and was unaware of the interview questions asked of students in the first study (School A), he was informed of the results of the study. As well as making evolutionary changes to his teaching strategies from his personal reflections on his practice, information about the first study would have influenced his subsequent interventions. Other differences between the schools were evident. In School A, there was tension between the specialist teacher and the generalist teacher over the style of classroom operations – the classroom teacher insisted on a group approach and discouraged explicit teaching. As there were seven special needs students in this group, in-class support for these students was provided by a teacher's aide and volunteer parents. The specialist teacher was unsure whether the children's responses to formative assessment activities were entirely their own work. In contrast, the three home class teachers in School B actively supported the visiting specialist teacher in his teaching approach. Similarly, in School C the home class teachers were supportive, although as discussed in the Method section, the intervention in School C was compromised by last minute changes to the school program, which meant the intervention was abbreviated.

Despite the potential for these differences to confound conclusions, we found that the range and nature of the children's responses in all case studies was remarkably similar. The written and audio recordings of the interviews revealed no significant difference between the substance and range of student responses obtained from the two interviewers (the authors). We contend that the differences between the schools are consistent with the obvious differences between the interventions: the lesser degree of understanding in Schools A and C is consistent with the fact that 25% of the class in School A had identified learning difficulties and in School C, the intervention was cut short allowing little time for consolidation of learning.

Discussion

Our results collectively show that 9 year olds enjoy science, want to know how the world works, and are seeking answers to the 'why' questions as well as to the 'what'. This learning is not temporary; it is remarkably robust with relatively little loss after 8 weeks in Schools A and B and with some concepts surprisingly consolidated and improved over that time without further classroom experience of those ideas. This occurred, albeit to varying degrees, in children with and without specific learning difficulties. Remarkably, in School C, the basic concepts of atoms and molecules as particles were retained after one year.

Do these results demonstrate real understanding or do they reflect low level recall? Our results (Table 13) suggest that most (64/74) primary aged children in our study are beginning to develop conceptual understanding that atoms and molecules are the components of matter. Of this group of 64, 50 described molecules as being made of atoms, and of the sub-set of 50, 24 knew that atoms were also composed of smaller particles. Many of this last group showed high level understanding of atomic and molecular structure. Guttman and McNemar tests revealed ordered connection between levels of understanding of atoms and molecules implying the formation of conceptual understanding rather than random recall of information about atoms and molecules. Significant retention in the short-term (eight weeks for Schools A and B) and in the longer term (one year for School C) also supports the proposition that Year 4 children in this study are beginning to form a conceptual framework about atoms and molecules.

In schools, we teach the symbolic alphabet at the beginning of formal education which allows children to form words, then sentences and ultimately sophisticated pieces of writing. Similarly, mathematics education begins with numbers and their symbols which are the building blocks of mathematics. Foreign languages are also best learned in the early years. If these symbolic languages are best learned whilst young, why do we leave atoms (and elements), which are the symbolic building blocks of our material world and the cosmos, until high school? Teaching primary aged children an explanatory model of matter and its properties would allow them to understand why things happen. Currently, the Australian primary curriculum deals only with the macroscopic observable properties of matter, surely a recipe for boredom if presented purely factually.

We hypothesise that it may be too late to leave the teaching of atomic-molecular theory until adolescence, when children have had 12 years of life and 7 years of schooling to develop their own naïve explanations of the macroscopic behaviour of matter. Developing children's interest and understanding of atoms and molecules in a spiral approach throughout primary school may lead to better science outcomes in secondary school and greater uptake of science related careers than the current educational model.

Further research needs to be done to challenge the assumption that because high-school students find atomic-molecular theory difficult it must be too difficult for primary aged children. We are currently exploring a number of questions;

- Can primary aged children apply knowledge of atoms and molecules to explain the properties and behaviour of matter?
- Can generalist primary teachers be trained to teach atomic-molecular theory?

The answers to these questions have significant ramifications for science curricula.

Conclusion

Atomic theory is a big theory that underpins much science, yet it is highly abstract. Traditional views of 9-year-old children's abilities would contend that they should not have been able to grasp this abstract concept; our data indicate that they can, they want to and they relish the intellectual challenge of doing so. As research has shown, this desire to know 'why' is a key factor in the pursuit of science as a career, and as that is a desirable outcome of STEM education, educators should be fostering this desire and minimising children's boredom with school science.

This study significantly challenges existing science curricula, which leave the big ideas of science until high school, when children have already begun to disengage with science. We suggest that the failure of science education to capitalise on the capacity of young children to understand fundamental concepts deprives them of explanatory tools that make sense of everyday phenomena and may be one reason why children continue to turn away from science. If this is the case, science education may be inherently unjust in its failure to develop the unrealized potential of our children.

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