New Ways of Learning Atomic Theory for 9 Year Olds: Educational Justice for Elementary Children

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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 or DNA. This research examines new ways of introducing atomic theory to 9 year olds and to verify their efficacy in producing genuine learning in the participants. Early results in two cases 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.

Purpose
Many countries, including USA and Australia, are looking to science and scientists for solutions to contemporary issues. President Obama and Australia's Chief Scientist, Professor Ian Chubb, have stressed the importance of investment in Science, Technology, Engineering, and Mathematics (STEM) to secure our continued social, economic, and cultural prosperity (Chubb, 2012, 2013, 2014; Obama, 2009, 2010, 2013). Both have championed the cause of improving science education, increasing time spent on science in elementary school (Chubb, 2013), and producing more highly qualified, respected and supported science teachers (Chubb, 2013; Obama, 2009, 2013).

Research indicates that children are most interested in science at age 10 with careers decided by age 13 or 14 (Tytler & Osborne, 2012), yet curricula (Australian Curriculum and Reporting Authority [ACARA], version 6, 2014; National Research Council [NRC], 2012, 2013) leave the big ideas of science such as atomic theory, DNA, natural selection until children are aged 14 or older. 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. We may be leaving it too late to introduce children to the exciting big ideas of science, the ideas that underpin scientific thinking, the ideas that explain how the world works and that satisfy curiosity. This educational injustice ignores the potential in today's children.

Narrow interpretations of Piaget's work infer that children cannot handle the big ideas of science until they develop abstract thinking at age 14; such interpretations have driven curriculum design. 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. This research has sought to verify these claims.

Perspectives
As well as justified concern over future numbers of scientists, there is an expressed need for a scientifically literate citizenry. Scientific initiatives need to be for all. An 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.

An Australian researcher (Jakab, 2013) had found that children aged 6-11 could articulate molecular level ideas about matter using appropriate artefacts. Support for working specifically with Grade 4 Australian children (average age 9 years) came from results from the Trends in International Mathematics and Science Study (TIMSS) in 2007. Australian Grade 4 children achieved above average overall, and shared positive attitudes towards science with the average for the 36 participating countries (Thomson, Wernert, Underwood, & Nicholas, 2007). Yet both attitudes and achievement were much lower in Australian Grade 8 children, with interest well below average. This raises the question: What happens between Grades 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, 2014) for Grades 4 to 8 deals with "what" questions. Chemistry deals with solids, liquids, and gases as separate entities, physical properties of materials, reversible and irreversible changes, 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 Grade 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?

Methods

This qualitative research used semi-structured interviews (Creswell, 2005), allowing 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. A pre, post, and retention interview protocol was utilised, with the last interview approximately 8 weeks after the classroom intervention ended. In the interviews, children could respond orally, by drawing, and by manipulating models. The first case involved 26 Grade 4 children (and one Grade 1 child present by parental request) in a Catholic primary school (School A) in Brisbane, Queensland, Australia. This was a diverse class with seven children with diagnosed special needs. The second case was carried out in another Brisbane Catholic school 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 third case was another Catholic school (school C) in a Year 4 class of 24 children who had some introductory lessons on atoms and molecules with the specialist teacher in the previous year.

The specialist science teacher, who is 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. This covered atoms, molecules, elements, the Periodic Table, subatomic structure, properties of metals and non-metals, electric charge, the octet rule and valence electrons. The intervention used pedagogy and new models designed and made by the specialist teacher. Because of circumstances in School C, the intervention in this school was curtailed to 5 weeks and involved a brief revision of atoms and molecules.

Informed consent for both 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.

Data sources
Primary data sources are the interviews subjected to content analysis to produce scores and thematic analysis to reveal commonly held conceptions and misconceptions. Secondary data sources for triangulation are the lesson reflections written by the specialist science teacher, and children's responses to fun tests administered in class.

Results and Discussion
1) Children's attitudes to and perceptions of science

Pre-interview data (Tables 1 and 2) reveal that elementary school is fertile ground for developing children's love 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/loved science because "It's fun"/interesting and satisfies their curiosity. The few who disliked science said it was too hard or they didn't like writing about it.

Table 1: Pre-interview responses to "What is science?" (Percent (rounded) of total responses)

Pre-interview responses from Schools, A, B and C	**Grade 4(A) N=26**	**Grade 4(B) N=24**	**Grade 4 (C) N= 24**
Discovering/learning how the world works	18	27	27
Experiments and practical activities	33	36	29
Atoms/molecules	2	0	21
Earth & space/physics	21	14	10
Animals/plants/medicine	14	18	4
Technology/making things	4	5	2
A school subject/don't know	5	0	6
Fun	4	0	0
Total (more responses than students)	**100**	**100**	**100**

Table 2: Pre-interview reasons for liking science (percent (rounded) of total responses)

Pre-interview responses from Schools A B & C	**Grade4(A) N=26**	**Grade 4(B) N=24**	**Grade 4(C) N=24**
Discovering/learning/how the world works	21	34	27
Doing experiments and practical activities	9	34	20
Learning about atoms/molecules	0	0	9
Learning about earth/space/physics/ animals/ plants	6	3	4
Interesting/ my favourite subject	24	12	9
Fun	41	10	29
Percent children who liked science (some gave more than one reason)	**100**	**93**	**98**

2) Children's prior knowledge of atoms and molecules

Children's prior knowledge was probed by asking, "Have you heard the word (atom/molecule)?" If they responded yes, they were asked, "Tell me what you know about atoms/molecules" and "Can you draw an atom/molecule and explain your drawing?" Children's answers about atoms and molecules were categorised into three levels of understanding as shown in Table 3.

Table 3: Pre-interview understandings of children (percent (rounded) of the class)

Pre-interview understandings from Schools A & B	Grade 4(A) N=26	Grade 4 (B) N=24	Grade 4(C) N=24
No understanding of atoms	92	83	21
Atoms ARE particles/building blocks of matter	4	17	71
Atoms are MADE of small particles	4	0	8
Total	**100**	**100**	**100**
No understanding of molecules	88	92	38
Molecules ARE particles	8	8	29
Molecules are MADE of atoms joined together	4	0	33
Total	**100**	**100**	**100**

Most Grade 4(A) and 4(B) children had no or minimal prior knowledge about atoms or molecules. Whereas with prior teaching in the previous year, 80% of children in Grade 4(C) understood that atoms were particles and 33% knew that atoms made up molecules.

These data suggest that without specific teaching, most 8-9 year old children have not yet developed an intuitive theory about the particle nature of matter.

3) Children's knowledge of atoms and molecules after a teaching intervention

In the post and retention interviews, children were asked the same questions that were asked in the pre interviews: "Have you heard the word (atom/molecule)?" If they responded yes, they were asked, "Tell me what you know about atoms/molecules" and "Can you draw an atom/molecule and explain your drawing?" Table 4 shows post and retention interview data for Grade 4 children comparable with Table 3.

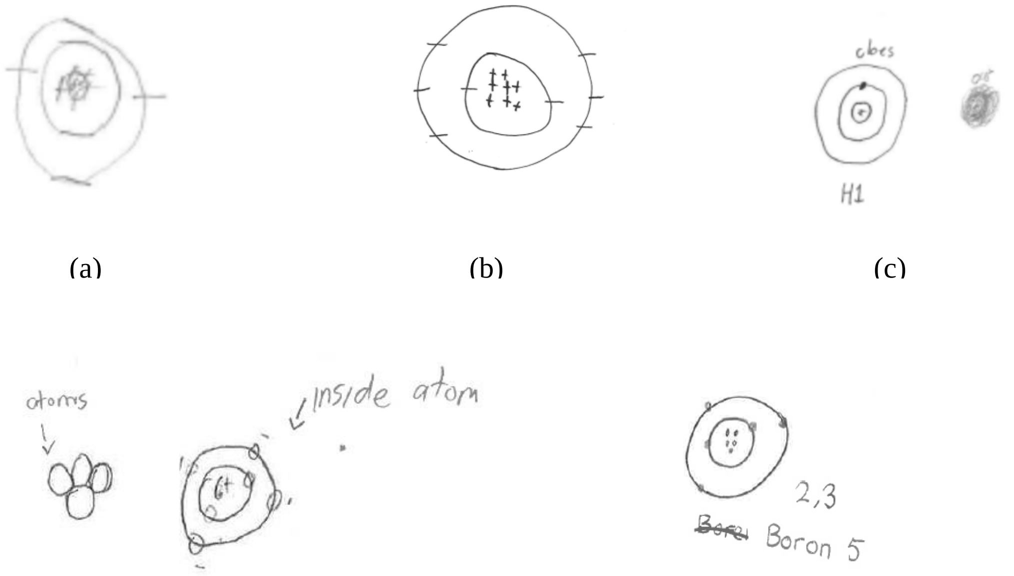
Table 4: Post and retention interview understandings of Grade 4 children (percent (rounded) of the class)

Post and retention interview understandings from Schools A, B and C	School A (N=26)		School B (N=24)		School C (N=24)
	Post	Retention	Post	Retention	Post
No understanding of atoms	4	8	4	8	4
Atoms ARE particles /building blocks of matter	46	58	33	38	79
Atoms are MADE of particles	50	34	63	54	17
Total	**100**	**100**	**100**	**100**	**100**
No understanding of molecules	31	23	4	12.5	4
Molecules ARE particles	15	15	17	12.5	42
Molecules are MADE of atoms joined together	54	62	79	75	54
Total	**100**	**100**	**100**	**100**	**100**

Comparing Tables 3 and 4 indicates Grade 4 children from all schools gained considerable understanding of the atomic nature of matter from the teaching intervention. In the post-interview, 96% of children knew that matter was made of atoms, with 50% from school A and 63 % from School B being able to describe the atom's sub-atomic structure. Only 17% in School C were able to discern the structure of an atom, which is an improvement from the 9% in the pre-interview, and this small gain in understanding is consistent with the lack of time for consolidating understanding in the truncated teaching intervention.

Figure 1 shows high level conceptual understandings in the post-interview drawings of seven children from Schools A, B and C.

Figure 1: Samples of children's post-interview drawings of atoms



(a) (b) (c)

(d) (e)

Grade 4(A)

(a) has correctly represented the carbon atom
(b) has correctly represented the oxygen atom
(c) has shown two representations of the hydrogen atom – an electron cloud drawing and a more detailed close-up picture of the sub-atomic structure of the hydrogen atom.

Grade 4 (B)

(d) has shown a cluster of atoms and a detailed drawing of the sub-atomic structure of the oxygen atom

Grade 4 (C)

(e) has drawn a correct representation of a boron atom

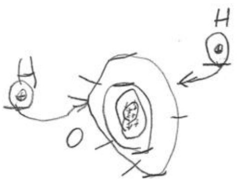
Ascertaining retention eight weeks later, 92 % of A and B retained the understanding that atoms are particles of matter. As expected, some children's understanding was not consolidated: 16% (School A) and 9% (School B) of the children who identified the sub-atomic structure of atoms in the post-interviews failed to do so eight weeks later. Nonetheless, one third of the class in school A and just over 50% of the class in school B 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 different nature of the cohorts. Seven children in school A had identified learning difficulties compared to one child in School B.

Our results suggest that most 9 year old children are able to grasp the concept that matter is particulate if it is explicitly taught. A smaller but not insignificant percentage, ranging from 34-63% in this study, can represent fundamental aspects of sub-atomic structure.

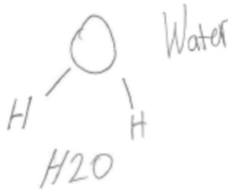
Understanding molecules is more challenging as atoms are pre-requisite knowledge. Table 4 shows that the percentage of children with no understanding of molecules is equal to or higher than the percentage with no understanding of atoms. Despite the extra conceptual complexity for molecules, 54% of the Grade 4 (A) class in the post-interview knew that molecules were composed of atoms and could draw accurate representations of molecules. It is interesting to note that this percentage increased to 62% eight weeks later. We have no clear explanation of why this happened except to suggest that the post-interviews may have prompted children to clarify their understanding. Children in School B, demonstrated a greater understanding that molecules were made of atoms in the post interviews (79%) with a small 4% reduction after 8 weeks. In School C, there was a 21% increase in understanding over a 4 week period from pre to post interview despite the limited nature of the intervention.

Figure 2 shows a sample of Grade 4 (A) and Grade 4 (B) children's drawings of molecules from post- and retention interviews, which clearly demonstrate understanding of the valencies of different atoms and how atoms combine to form molecules. The drawings of Grade 4 (C) children were similar to (g) and (h).

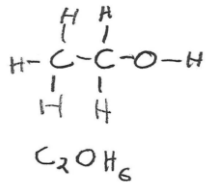
Figure 2: Samples of children's post and retention interview drawings of molecules



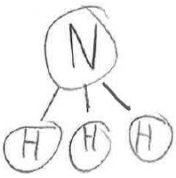
(f)



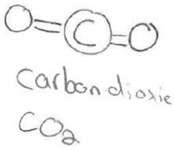
(g)



(h)



(i)



(j)

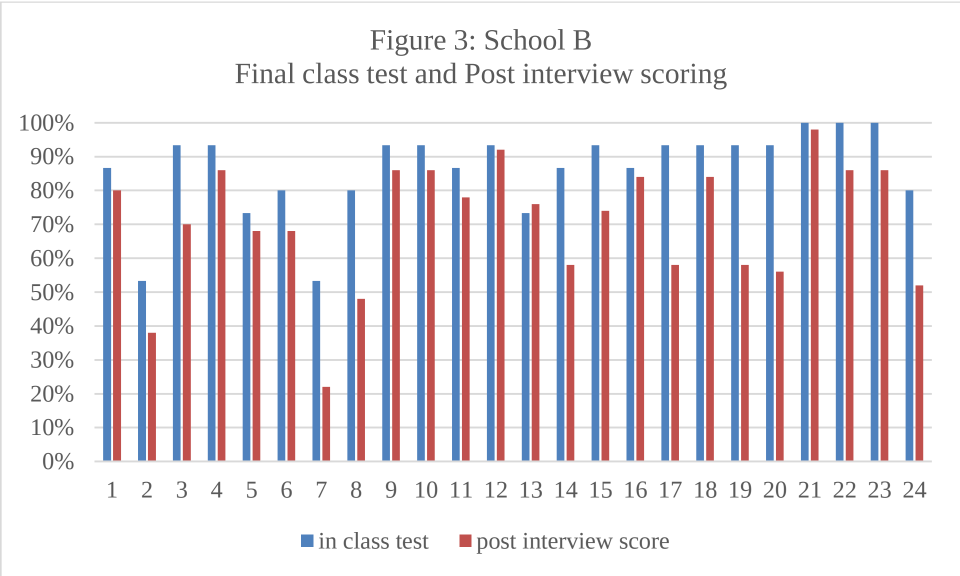
Grade 4(A)
(f) has shown how the water molecule is formed by the sharing of the electrons of hydrogen atoms in the outer electron shell of oxygen. This student shows exceptional thinking.
(g) has correctly represented the structural and molecular formula of water
(h) has correctly represented the structural and molecular formula of ethanol

Grade 4(B)
(i) has correctly represented the structural formula of ammonia
(j) has correctly represented the structural and molecular formula of carbon dioxide

The analysis presented here clearly demonstrates young children's great interest in and desire to understand how the world works. It also indicates their capacity to understand the atomic and molecular nature of matter and to retain this knowledge, even after a period of up to one year.

Classroom test

Children's responses to the post interview questions were scored and compared to the grades awarded in the final in-class test. These results, expressed as a percentage are shown in Figure 3 for school B.



The graph 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, children's responses in the 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 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 his practice indicates that he regularly checked for understanding though 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.

Limitations of the study

This study is not an experimental study 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 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.

Conclusion

Our case studies collectively show that 9 year olds enjoy science and want to know how the world works, i.e. they 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 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. 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.

Significance

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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