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A Picture is Worth a Thousand Words: Investigating First Year Chemistry Students' Ability to Visually Express Their Understanding of Chemistry Concepts

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Abstract

Within a large first year chemistry cohort we identified that students were routinely expressing their understanding of chemical processes invariably at the macro and symbolic levels of representation, but rarely at the 'submicro' level. This observation is consistent with a wealth of previous literature on this topic, identifying students' inherent difficulties in imagining atomic-scale processes appropriately, and their ability to interconnect their imagined reality to macro-scale, observable chemistry. This paper aims to describe how a classroom intervention was used to explore student misconceptions at the macro and submicro level of chemical processes. Specifically, a method was sought for measuring the level of understanding in a large first year chemistry cohort. The investigation involved a review of the relevant chemistry education literature, student interviews, and the collection of over three hundred student-generated drawings that were produced solely from the imagination of the participants. The outcome of this work includes the generation of criteria sets enabling the measurement of student understanding, which align with common misconceptions identified for a series of specific tasks. However another key finding is that such tasks should not be conducted in the absence of class discussion, since what students convey through drawing chemical scenarios does not usually depict a complete picture of what the student truly understands, as we identified through student interviews. Nevertheless, the implication of this work is that student-generated drawings play an important role is both diagnosing, and helping students overcome common misconceptions associated with atomic-scale processes in chemistry.

Introduction

This introduction provides a review of the chemistry education literature relating to this study in four sections. The first section discusses the macro, submicro and symbolic levels of representation and their importance in communicating and understanding chemistry drawing on available academic literature in the field of science education. The second section, also drawing on this literature, gives a general overview of alternative conceptions and how they can impede students' progression towards understanding chemistry concepts with reference to a specific empirical research study. The third section reviews the two useful diagnostic tools for identifying alternative conceptions amongst students and the results that were determined from students' responses. The last section discusses the benefits of using student-generated submicro drawings as learning tools that can be concluded from this study.

The triplet relationship

Knowledge and understanding of chemistry may be expressed using three ‘levels’ of representation commonly referred to as the *macro*, *submicro* and *symbolic* levels (Johnstone, 1991) with the term *triplet relationship* used to cover all three (Gilbert & Treagust, 2009). A chemical reaction can, using examples, be represented at the macro level through observable phenomena such as colour and temperature change; at the symbolic level with mathematical and chemical equations and at the submicro level by representing atoms and their derivatives using particulate drawings or building molecular models (Gilbert & Treagust, 2009). Johnstone (1993) recommends that chemistry instructors engage students at all three levels of representations as they provide a useful framework for understanding and teaching chemistry. Treagust, Chittleborough, and Mamiala (2003) argue that while each level plays a role in describing and explaining a phenomenon, it is the ability to both understand and easily shift between all three levels that is necessary for developing a good understanding of chemistry. However, research has shown that many instructors tend not to highlight how the three levels are inter-connected, and as a result, students are often unable to understand how they link together (Gabel, 1999). While most chemistry teaching occurs at the macro and symbolic levels, many alternative conceptions stem from an inability to visualize structures and processes at the submicro level (Tasker & Dalton, 2006; Tasker (2008); Tasker (2013)).

Alternative conceptions

The intangible nature of chemistry makes it a difficult subject for students to learn and as a result students tend to hold a variety of alternative conceptions (Garnett, Garnett, & Hackling, 1995). Although the term alternative conceptions will be used in this paper to describe ideas that differ from the commonly accepted scientific consensus, a review of the chemistry education literature has shown that experts use a variety of terms (Abimbola, 1988). The two most commonly used terms, *alternative conceptions* and *misconceptions*, are often used synonymously (Horton, 2007; Taber, 2000). Alternative conceptions may arise from a variety of personal experiences students have with their physical and social environments including direct observation and perception, instructors, language, textbooks and peers (Wandersee, Mintzes, & Novak, 1994). Alternative conceptions can also interfere with the learning of correct scientific ideas and can be highly resistant to change with instruction (Novak, 1988). A literature review of alternative conceptions related to chemistry by Horton (2007) reported that alternative conceptions held by students can be very slow to change after the age of 12 and are likely to still be present at age 18, and may remain throughout life. An example is the alternative conception that water molecules undergo a chemical change rather than a physical change during the transition from the liquid to the gaseous state. A study by Mulford and Robinson (2002) reported that only 39% of students entering a first year chemistry course (45% at the end of the first semester) considered that when water evaporates the water molecules move further away from each other; 37% of the participants (41% at the end of the first semester) considered that intermolecular bonds were broken resulting in hydrogen and oxygen atoms and/or molecules being formed. This alternative conception has been reported in numerous other studies including at the tertiary level by Potgieter and Davidowitz (2011) and at the secondary level by Osborne and Cosgrove (1983).

Diagnosing alternative conceptions

According to the constructivist theory of learning, knowledge is actively constructed by individuals through personally meaningful experiences that enable them to connect new knowledge to what they already believe or understand (Killen, 2009). Students bring to university existing knowledge structures into which new experiences must be integrated (Potgieter & Davidowitz, 2011) and an implication of constructivism is that for teaching to be effective, students' prior knowledge must be taken into account (Duit, 1996). It is therefore important to try to identify students' alternative conceptions and then devise remediation strategies that help in the development of more effective learning environments (Özmen, 2004).

A review of the chemistry education literature reveals two useful diagnostic tools for identifying and raising awareness of alternative conceptions amongst students are chemistry concept inventories (CCI) and student-generated diagrams. Both diagnostic tools can be used to assess knowledge and conceptual understanding across the symbolic, macroscopic, and submicro levels of representations (Bunce & Gabel, 2002) and are useful for gauging the effectiveness of instruction and improving curriculum design (Smith & Metz, 1996). While CCI items provide for quick and easy formative feedback to help students identify concepts that they need to address (Lawrie, G., Wright, A., O'Brien, G., Bedford, S., Schultz, M., Dargaville, T., Williams, M., Tasker, R., Dickson, H. & Thompson, C., 2013), Smith and Metz (1996) suggest student-generated drawings could uncover a greater range of alternative conceptions and lead to more informed teaching and improved student conceptual understanding. Nyachwaya et al. (2011) argue that compared to CCI questions, student-generated drawings require students to express their understanding of a concept to a greater level of depth, effectively shifting the nature of students' thinking from 'choice-making' to 'sense-making'. Other disciplines such as physics education have similarly shown benefits to students through not being passive learners, but instead engaging in active-learning strategies such as Interactive Lecture Demonstrations (Sharma et al., 2010; Tanahoung et al., 2009).

Student-generated submicro diagrams

Diagrams are beneficial learning tools in many disciplines (Stieff, Bateman Jr, & Uttal, 2005). However, while chemistry students commonly encounter submicro representations in texts, animations and teaching, their ability to understand and draw accurate representations to explain or respond to questions has been shown to be less than satisfactory for many students (Davidowitz, Chittleborough, & Murray, 2010; Kelly & Jones, 2008). Davidowitz et al. (2010) suggest that student-generated submicro drawings should be used more routinely as a learning tool rather than simply as illustrations in text books and questions at the end of chapters. This would enable students to make links between the submicro and symbolic levels, allowing them to fully interpret the information implied in a chemical equation. In addition, problems that require students to draw diagrams require a higher order of thinking than using algorithms, which can be used to answer questions through a recipe driven approach. A significant fraction of problem solving questions given to students in introductory chemistry courses are focused on quantitative problems that can be solved algebraically. However, a greater number of problems that practicing chemists encounter are more likely to be non-mathematical, such as predicting the product of a reaction, envisioning a reaction mechanism, interpreting NMR or IR spectra and designing experiments (Bodner & Herron, 2003).

Despite the increasing frequency of submicro diagrams in introductory text books, there has been little research into the use of student-generated drawings when teaching about chemical reactions, including equations and stoichiometry (Davidowitz et al., 2010). However, research in this area using student-generated submicro drawings in conjunction with submicro animations has been reported to significantly increase students' ability to represent key features of submicro particles (Tasker & Dalton, 2006). Smith and Metz (1996) argue that using student-generated drawings as a teaching strategy could increase conceptual understanding by providing students with a way of visualizing and developing a mental model for a concept, suggesting however that adequate guidance should be provided. If adequate guidance is not provided, then as an example, a student may depict a chemical reaction by drawing a single particle when in reality many particles are present. Ben-Zvi, Eylon, and Silberstein (1988) found that when some students were asked to interpret the symbolic meaning Cl_2 (g), they viewed Cl_2 (g) as representing one molecule because they did not recognize that (g) represented chlorine in the gaseous state where large numbers of Cl_2 molecules are present.

Research Questions

We aimed to explore student misconceptions around atomic-scale chemical processes by asking the following questions:

1. Can student-generated drawings reveal misconceptions about chemical processes in aqueous solutions and precipitates?
2. Can the outcomes of student-generated drawing tasks be used to measure the level of student understanding across large student cohorts?

Context and Methods

The participants for this study were first year general chemistry students at a large university in Victoria, Australia, all of whom had completed senior secondary chemistry. Data was gathered via two approaches, a questionnaire and dynamic visual interviews.

The questionnaire

The study involved 305 participants who attempted two items (Figure 1) from a questionnaire during week 1 of semester 1, 2013. As year twelve is the highest level of secondary education in Australia, the participants should have had the knowledge to adequately answer the two items. The questionnaire was completed by pen and paper, with data categorised using the criteria described in the results section below.

Item One:

When a dilute solution of silver nitrate (Ag^+ and NO_3^-) is mixed with a dilute solution of calcium chloride (Ca^{2+} and Cl^-) a white precipitate silver chloride is formed. In the space provided below write a **balanced** chemical equation that represents this reaction.

Item Two:

Draw a diagram that represents how you imagine the atoms, ions and molecules of the **products** from question 1 (solid silver chloride and aqueous calcium nitrate) would look like if you could see them. Include the solvent (water).

Figure 1: The two items from the questionnaire

Dynamic Visual Interviews

At the end of semester 1, 2013, four students who had completed the questionnaire participated in a dynamic visual interview. This phrase is used to describe a largely unscripted interview using an interactive whiteboard, where think aloud protocol (Bowen, 1994; Cheung, 2009) is used to capture the thought processes of students as they work through a chemistry problem. The audio is captured and transcribed for coding analysis.

Results and Discussion

The questionnaire

Students were invited to attempt the two items shown in Figure 1 after being informed that it was part of a research project and therefore, participation was voluntary, completely anonymous and that participants could opt out at any point with no consequences.
Item one in Figure 1 was worded so that participants could demonstrate an understanding of how coefficients, subscripts and physical states are used when fully balancing an equation. Item two was chosen specifically because it required participants to distinguish between varieties of bonding that they would have learnt about in their previous studies of chemistry. Participants were provided with a legend and encouraged to provide written explanations for their diagrams which were taken into account when assessing the representations.

In order to adequately evaluate the collection of approximately 300 student drawings, we set out to develop a robust set of criteria. The criteria were developed using a grounded approach which enabled themes to emerge by coding and categorizing the drawings through repetitive comparison.

Item two omitted guidance to include detail such as molecular geometry, charges or how bonds should be represented so that participants' responses did not incorporate ideas they would have not normally considered on their own. Therefore, participants' drawings were able to be interpreted unambiguously as a visual expression of their understanding and not an artefact of the way the item was worded. The subsequent interviews gave four participants the opportunity to express explicitly an understanding of a concept that they may have chosen not to include on their original diagrams. This was important because without explicit explanations into their reasoning it is possible for students' drawings to be misinterpreted (Tien, Teichert, & Rickey, 2007).

Item one

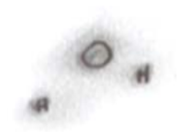
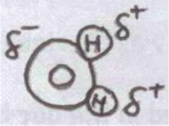
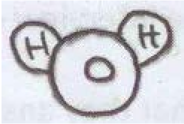
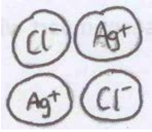
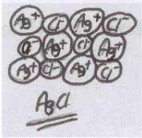
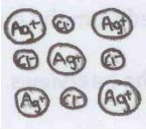
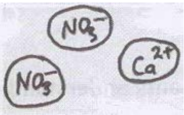
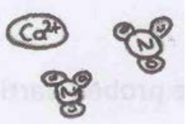
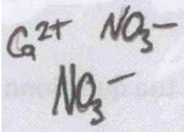
Sixty five percent of the participants were able to correctly balance the equation and include the physical states. The number of correctly balanced equations increased to 82% when taking into account participants who did not include the physical states. The data from item 1 revealed that 68% of the participants who correctly balanced the equation and included the physical states visually represented the reaction as a multiple particle process. However, only 35% of participants who correctly balanced the equation but did not include the physical states visually represented the reaction as a multiple particle process.
The significance of this statistic is that if the meanings of chemical equations and the associated physical states are not fully understood by a student then they may have a poor understanding the interactions between submicro particles. As pointed out by Bucat and Mocerino (2009), for a good understanding of chemistry it is critical that students visualise chemical reactions at the submicro level as a multiple particle process.

Item two

Comparing the data from both items revealed a large disparity between participants' ability to represent the reaction using an equation and a submicro drawing. Student drawings revealed that many participants' had trouble visually expressing their understanding of the structure and properties of atoms, ions and molecules and how they interact with each other. Many participants did not represent water molecules in any great detail and were therefore not able to express an understanding of the role of water in dissolving and hydrating ions during the dissolution process. Participants' representations for silver chloride revealed that many had trouble visualizing ionic solids consisting of individual ions by instead drawing molecules, ion pairs or atoms. Similarly with aqueous calcium nitrate many participants visually expressed an understanding that ionic solids dissolve as molecules, ion pairs or atoms.

The criteria used for cataloguing each students' questionnaire was developed using the same approach as Nyachwaya and coworkers (2011), and cross referenced by the chemist authors on this project. Criteria were developed to assess participants' drawings for the three themes of water; solid silver chloride and aqueous calcium nitrate. These are listed in Table 1 along with the percentage of drawings that met all the criteria and examples. Figures 2-5 provide examples that did not meet one or more criterion for water, solid silver chloride and aqueous calcium nitrate respectively. All representations met the 'correct formula' criterion if they were identified and matched the correct formula from the balanced equation, for example by including the chemical symbol. All representations for ions met the 'charges are shown and correct' criterion if they indicated the correct charge, for example by using '+' or '−'signs.

Table 1: Drawings that met all criteria for each compound

Criteria	Examples			Criteria met
1. Covalently bonded molecules 2. Correct relative atomic sizes 3. Bent molecular geometry 4. Correct formula				28%
1. Alternating cations and anions 2. Charges are shown and correct 3. Correct formula				9%
1. Dissociated ions 2. Charges are shown and correct 3. Correct formula				19%

Representations for liquid water

Kelly & Jones (2008) concluded from their study that students need frequent reinforcement of what scientific terms such as aqueous and water soluble mean. They believe that water molecules should be included in student-generated drawings of solutions to help students understand the role of water in the dissolution process. They argue that because textbook diagrams often represent the solvent as a continuous fluid, students can be unaware of the importance of the interactions between the solute and the solvent. Therefore, item two specifically asked participants to include representations of water molecules to allow participants to demonstrate their understanding of solvent-solvent and solvent-solute interactions.

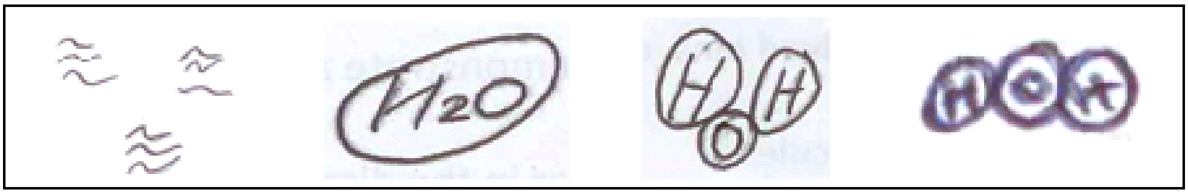


Figure 2: Drawings not meeting one or more criterion for liquid water

Participants' drawings of water molecules were considered to have met the 'covalently bonded molecules' criterion if they depicted individual shapes for hydrogen and oxygen atoms that were overlapping, touching or connected by lines; or chemical symbols connected by lines. Drawings that met this criterion provided the detail required for participants to express an understanding of the role of water in dissolving and hydrating ions during the dissolution process. Some drawings indicated detail such as partial charges on atoms; however this did not develop into a separate criterion because an understanding of directional bonding was able to be expressed without partial charges being indicated.

The 'correct relative atomic sizes' criterion emerged because knowing that a hydrogen atom is smaller than an oxygen atom is not just a superficial difference. The periodic trends in atom and ion sizes are, like electronegativity, accounted for by comparison of the effective nuclear charge. Therefore, students should be aware that the sizes of atoms are related to their electronegativity which in turn influences properties such as melting and boiling points, solubilities and reactivity. The importance of diagrams indicating a reasonable representation of the relative differences in ion sizes has been recommended by Coll and Treagust (2003). Although the difference in relative atomic sizes for hydrogen and oxygen atoms is something that participants should have been familiar with, knowing this difference for silver chloride and calcium nitrate did not emerge as a separate criterion as knowing the relative differences in these ion sizes is something that participants were not familiar with.

Representations for solid silver chloride

Participants' drawings for solid silver chloride met the 'alternating cations and anions' criterion if they depicted alternating ions using chemical symbols or shapes drawn either touching or in close proximity to each other. Drawings were considered to have not met this criterion if they depicted molecules or ion pairs; ions connected by a line were only considered to have met the criterion if indicating they were part of an ionic lattice.

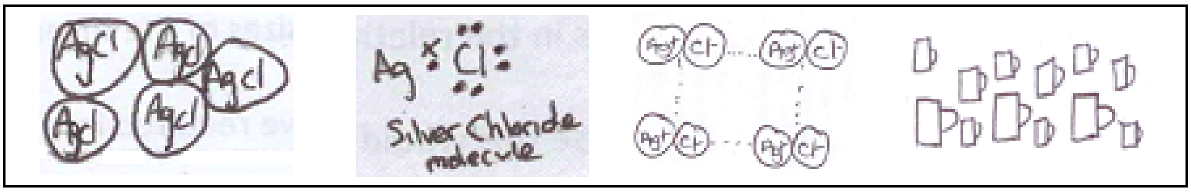


Figure 3: Drawings not meeting one or more criterion for silver chloride

Representations for aqueous calcium nitrate

Participants' drawings for aqueous calcium nitrate met the 'dissociated ions' criterion if ions were depicted using chemical symbols or shapes that were clearly separated from each other, even if water wasn't depicted. Drawings did not meet this criterion if the shapes or symbols were touching, overlapping or connected by a line. It was considered that these types of representations indicated that participants had an understanding that calcium and nitrate ions existed as molecules or ions pairs in solution.

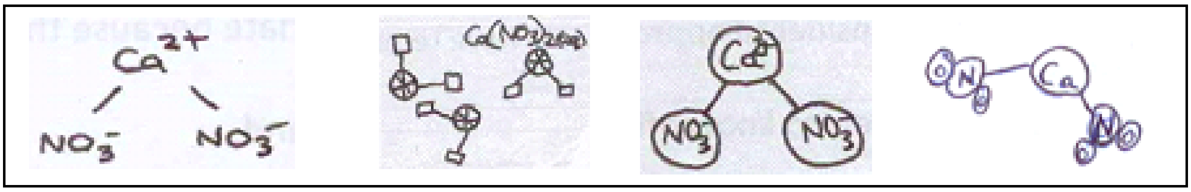
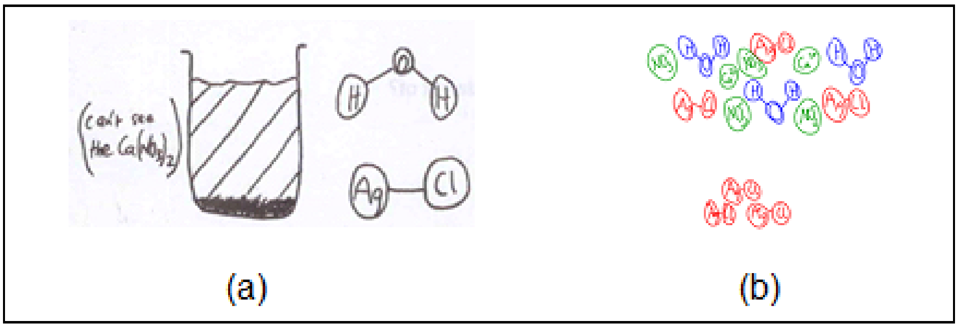


Figure 4: Drawings not meeting one or more criterion for calcium nitrate

Dynamic Visual Interviews

For this study we used *dynamic visual interviews*. This type of interviewing technique is, as defined by the authors of this paper, a semi-structured recorded interview in which participants explain their understanding of concepts while the interviewer assists them to explore their meanings. During the interview participants produce visual data to support their explanations by using technology such as interactive whiteboards or tablets which allow digital copies to be saved for future analysis. For this study interactive whiteboards were used during the interviews.

Approximately twelve weeks after initially attempting items one and two from the questionnaire (Figure 1) four participants were again asked to attempt these items. Initially, all the participants drew diagrams that were similar to what they had drawn at the start of the semester. These drawings were appropriately modified after probing by the interviewers revealed that a deeper understanding was held for some concepts. Figure 5 shows the diagrams drawn by one of the participants, given the pseudonym *Krypton*, from the start of the semester (a) and the interview (b) and is followed by part of the interview transcribed verbatim. The diagrams in conjunction with the interview transcript indicate that Krypton held a commonly reported alternative conception that ionic solids consist of ion pairs.



(a)

(b)

Figure 5: Krypton's diagrams from; (a) start of semester; (b) the interview

Interviewer: *What type of bonding is there between your drawings for silver chloride?*
Krypton: *That's ionic bonding.*
Interviewer: *What do the lines between the silver and chloride ion represent?*
Krypton: *They represent an ionic bond.*
Interviewer: Why is there only one line between each silver and one chloride ion?
Krypton: *The line represents to me where it was that electrons were being transferred from and where they were ending up. It is sort of like a bookkeeping exercise for where electrons are moving to.*
Interviewer: *Do you think that by connecting a silver and chloride ion by a line that they exist as a molecule?*

Krypton: *I don't see silver and chloride ions connected by a line as a molecule, they are individual ions attracted to each other.*

Taber (1998) reported on an alternative framework of logically connected alternative conceptions known as the 'octet framework', the key principle of which is the 'full shells explanatory principle'. The principle may be explained in terms of atoms having a drive to achieve full outer shells and derives from students commonly over-generalising the octet rule from being a heuristic for identifying likely stable species, to a general purpose explanation for why reactions occur. Taber, Tsaparlis, and Nakiboğlu (2012) suggest that the alternative 'molecular framework for ionic bonding' fits into the broader 'octet framework' which students use to make sense of ionic bonding by considering an ionic lattice to consist of ion pairs or molecules. This framework can be summarised using the following three conjectures:
The valency conjecture: For example a sodium atom can only donate one electron, so it can only form an ionic bond to one chlorine atom.

The history conjecture: For example a chloride ion forms an ionic bond specifically to the sodium ion that donated an electron to it, and vice versa

The just forces conjecture: For example a chloride ion forms an ionic bond with one sodium ion but not to the other sodium ions that surround. The ion pairs are attracted to each other by some other, generally weaker, force of attraction.

The result is that students focus on ionic bonding as being an electron transfer event. So much so that when asked about precipitation reactions, students have explained them as being due to electron transfer between chemical species in solution, even after acknowledging those same species were already present in the solution (Taber, 2002). This alternative conception was held by another of the interview participants, given the pseudonym Neon. Figure 6 shows Neon's diagrams from the start of the semester (a) and the interview (b) followed by part of the interview transcript typed verbatim.

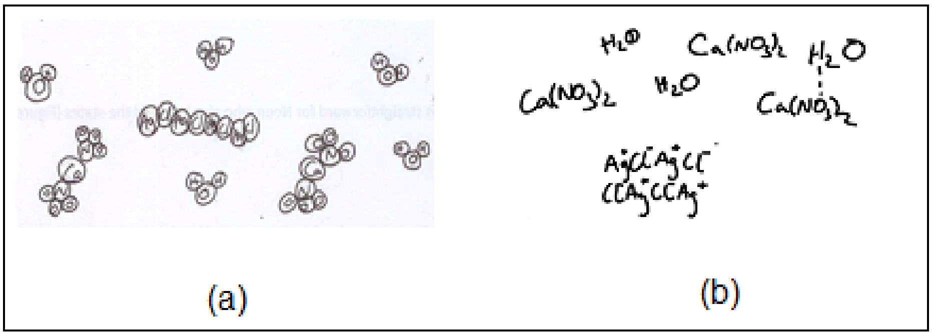


Figure 6: Neon's diagrams from; (a) start of semester; (b) the interview

Interviewer: *What type of bonding is there between the calcium and nitrate symbols?*
Neon: *It is ionic bonding.*
Interviewer: *Why do you think that it is ionic bonding?*
Neon: *The ions are joined together in solution. Calcium is a metal and it wants to give electrons to the nitrogen atom to form an ionic bond.*
Interviewer: *How do you imagine the calcium and nitrate ions in an aqueous solution interacting with each other?*
Neon: *I imagine that the calcium ion would be joined to two nitrate ions.*

The interviews highlighted that the use of student generated drawings, in conjunction with group discussion, are a valuable learning tool for students and the development of their conceptual understanding. The interviews also highlighted that the participants needed more guidance in how to draw submicro representations.

Implications

This study was specifically driven by our observation that students routinely have opportunities to *do* chemistry (via the laboratory program), have ample opportunities to represent the chemistry they do symbolically and in written form, but are rarely asked or required to demonstrate their imagined reality of chemistry at the submicro level. This is despite the fact that many chemical processes can only be properly understood by appreciating the behaviour of particles at the atomic scale.

The work presented here has implications for the tasks that sit alongside practical classes in chemistry. There is a potential benefit in coupling the hands-on activities in the laboratory with questions like the ones presented to students in this study, to help make the connections between the observable and the non-observable. We add that caution should be taken to ensure students have a clear understanding of how to represent atomic-scale particles appropriately, and that these should be coupled with classroom discussion to tease out the meaning behind what has been drawn.

Conclusion

This paper has discussed the initial stage of an investigation aimed at understanding students' ability to visually express their understanding of chemistry concepts. The data reported in this paper was subsequently used to inform the introduction of student-generated drawing questions into a first year chemistry program. A development that emerged from this initial stage was a criteria framework that could be used to categorize students' alternative conceptions based on their drawings. The framework allowed for a quick way to group participants' drawings and assess areas where a particular student may hold an alternative conception. Interviews were an important feature of this investigation and highlighted the importance of having a follow-up discussion with students about their drawings and what understanding they were trying to convey. The interviews also indicated that the participants needed more guidance in how to draw submicro particles and that future drawing tasks would require a degree of scaffolding. It was concluded from this initial stage that asking students to attempt drawing submicro diagrams, then to use them to facilitate a shared understanding with their peers in the presence of an expert, is an important pedagogical strategy for developing students' conceptual understanding.

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