This is the published version (version of record) of:


Available from Deakin Research Online:
http://hdl.handle.net/10536/DRO/DU:30025036

Reproduced with the kind permission of the copyright owner.

Copyright : 2010, University of Kwazulu-Natal
What can student-generated diagrams tell us about their understanding of chemical equations?

Bette Davidowitz 1 Gail Chittleborough 2 Eileen Murray 1

1 Department of Chemistry, University of Cape Town, South Africa 2 School of Education, Deakin University, Melbourne, Australia

Bette.Davidowitz@uct.ac.za; Gail.Chittleborough@deakin.edu.au; Eileen.Murray@uct.ac.za

Chemical equations are representations that use symbols to summarise the net changes occurring in a reaction whereas depictions such as drawings of the submicroscopic level provide representations of the chemical transformations. While the ability to balance and interpret chemical equations is key to understanding many concepts in chemistry, many undergraduate chemistry students struggle to master these skills. The equations contain a great deal of implicit information and novices may not be able to make the connection between the equation and the actual chemical transformations that are occurring. This paper reports on a study which used submicroscopic diagrams to probe students’ understanding of chemical equations. Assessment tasks required students to interpret diagrams, construct diagrams and to relate diagrams to symbolic representations. The analysis showed that some students have misconceptions about the molecular nature and chemical formulae and could not distinguish between coefficients and subscripts when representing chemical formulae. While students were generally able to balance a chemical equation presented as a set of diagrams, a significant number could not generate the balanced equation based on a diagram of the progress of a reaction. The study has demonstrated the use of student-generated diagrams to provide insight into students’ understandings of chemical equations.

Background

The chemical equation is a fundamental concept of the discipline. At first glance it appears simply to be a set of symbols but each balanced equation contains a great deal of information which is implied rather than explicit. Balanced chemical equations summarise chemical reactions and do not show details such as the spectator species or the reagent in excess. Novices see balancing equations as the application of a set of rules and may not make the connection between the symbolic representation of the reaction and the actual chemical transformations that are occurring (Laugier & Dumon, 2004). In addition, they may have difficulties in producing and interpreting equations due to a lack of conceptual understanding (Taber & Briheno, 2009). Authors of undergraduate textbooks often include diagrams containing multiple representations of the information contained in a balanced equation (Silberberg, 2009, table 3.5, page 110). These diagrams may appear trivial to the expert chemist but for a novice they contain much information about the chemical reaction at both the submicro and symbolic levels presented in multiple representational formats.

It is important for students to understand the information implicit in a chemical equation since the balanced equation forms the basis of many of the concepts which will be covered in a typical first-year chemistry course. Traditionally teaching of chemical reactions has focussed on the symbolic level of representation relying heavily on algorithms. Despite the increase in frequency of diagrams depicting the submicroscopic world in first-year chemistry textbooks, there has been little research into the use of student-generated drawings of the submicro level when teaching chemical equations and other basic concepts. The current study forms part of a larger project which examines the use of submicro diagrams in teaching and assessment of chemical equations and related topics.

Theoretical framework

In 1993, Johnstone described a model of the nature of chemistry consisting of three complementary levels: macro, submicro and representational (symbolic). While expert chemists are able to interpret diagrams representing images and information about the macro, submicro and symbolic levels, the connections between levels can be misinterpreted when students do not understand them or cannot construct the links between them. Johnstone’s three levels of representation provide a useful framework for understanding and teaching chemistry. Research using submicro diagrams has shown that this level
presents difficulties for novice learners. For example Nurrenbern and Pickering (1987) used diagrams depicting the submicro level of chemistry and showed that while students could solve algorithmic chemistry problems, they had difficulties in answering conceptual problems based on the same topics. Ben-Zvi et al. (1987) analysed students answers, including students’ diagrammatic representations of the structural aspects of chemical reactions and reported that many students were “unable to understand correctly a simple chemical equation” with some students holding “wrong ideas about both the structure and about the interactive nature of chemical reactions” (p.118).

The chemical equation, which lies at the heart of important concepts such as reaction stoichiometry and chemical equilibrium, has been identified as a difficult topic for learners over many years (Hackling & Garnett, 1985; Huddle & Pillay, 1996; Fach et al., 2007). In any given cohort of students there will be a vast range of abilities of students who can both balance an equation and understand the implied meaning in terms of macroscopic and submicroscopic levels (Huddle & Pillay, 1996; Laugier & Dumon, 2004). Marais & Jordaan (2000) investigated the challenge in interpreting the symbols in a chemical reaction for students who may have difficulties in distinguishing the difference between coefficients and subscripts. They found that only 7.4% of students knew that 2NO2 referred to two molecules (or two moles) of NO2. The authors suggest that chemistry teachers should realise that students may have difficulties in interpreting symbols and urge them to specifically teach the symbolic understanding which all chemists use as part of their discourse.

Being able to solve problems involving chemical reactions requires both applying rules and having an understanding of the concepts that give the rules meaning (Huddle & Pillay, 1996). The chemical equation is not the same as a diagram of the submicro level which may include representations of molecular, atomic and sub-atomic particles. Focussing on this difference is a pedagogical approach that requires active student-centred problem-solving tasks. These can provide opportunities for students to demonstrate their understanding which may inform future teaching. A strategy which focussed on using submicro diagrams to provide students with a foundation on which to build ideas such as balancing and understanding chemical equations was adopted at the University of Cape Town, UCT (Davidowitz & Chittleborough, 2009). Students are given opportunities to practice drawing and interpreting diagrams during the tutorial sessions which focus on chemical equations. Since submicro diagrams are an integral part of the teaching methodology of the course, they were subsequently used as an assessment tool to determine whether they could reveal any other misconceptions held by students.

Davidowitz and Chittleborough (2009) found that 63% of a cohort of students at UCT was able to write an appropriate balanced equation for a simple chemical equation presented as a submicroscopic representation. This compared favourably with the low number of correct responses (15%) reported by Sanger (2005) who used a free response question based on Nurrenbern and Pickering’s (1987) particulate drawing to evaluate students’ conceptual understanding of balanced equations and stoichiometric ratios. The results of the UCT study suggest that allowing students to engage with the material using multiple representations as recommended by Johnstone (1993) has been instrumental in the improved performance of students relative to the study reported by Sanger (2005). Further investigations at UCT compared students’ ability to balance equations and determine the limiting reagent in reactions depicted in terms of symbols or diagrams (Davidowitz & Chittleborough, 2009). The findings revealed that most students were capable of solving problems using an algorithmic-style problem-solving template, (Davidowitz & Chittleborough, 2009, Fig. 8.10) while they find it more difficult to do so using submicro representations despite the opportunities to practice using these representations in tutorials. This finding demonstrates the greater intellectual challenge involved in interpreting the diagrams relative to problems involving only symbols as noted by de Jong and van Driel (2004) and Treagust and Harrison (1999).

This paper reports on a study which extends the work described above and investigated the use of submicro diagrams to further probe students’ understanding of chemical equations. Assessment tasks contained questions requiring students to construct their own diagrams, to interpret diagrams and to relate diagrams to symbolic representations.

Methodology used

Sample

The participants in this study are two cohorts of first-time entering students registered in the General Entry for Programmes in Science (GEPS) at UCT. These students are from disadvantaged backgrounds and are considered to be under-prepared for tertiary study. They register for an extended BSc programme
and complete their degree over 4 years instead of 3. GEPS offers an adjusted curriculum that takes into account poor preparation at school, particularly in Mathematics and Science, as well as the fact that the majority of the students do not speak English as their first language. The underlying philosophy of the chemistry course is the teaching of fundamental concepts. There are 5 contact periods per week consisting of 3 lectures and 2 small-group tutorials. The teaching strategies were consistent across the two cohorts who were taught by the same lecturer using similar course materials.

Data sources

The data consists of students' answers to selected questions about chemical reactions posed in class tests and examinations. Permission was sought from students to copy their answers. Two of the researchers constructed a coding scheme to classify the answers to the test and examination questions. Where a difference arose, the category was determined by discussion and consensus. The latter happened in only a few cases. The responses to the questions were then analysed by the three researchers and comparisons made within and across cohorts allowing common misconceptions to be identified and providing evidence of the methods students used to reason and process information. A description of the tasks follows.

Question 1 was answered by the 2008 cohort, \( N = 164 \), and consisted of two tasks based on the same submicroscopic diagram, see Figure 1 below. Question 1a appeared in the first class test which was written after about 6 weeks of instruction, Question 1b formed part of the examination at the end of the first semester which occurred after 12 weeks of instruction.
Consider the reaction below:

Key: ○ Hydrogen ● Oxygen

Q1a For the reaction shown above, draw the correct number of each molecule after the reagents have been converted into a product. The balanced equation is:

\[ 2 \text{H}_2(g) + \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(g) \]

Q1b i) Write a balanced equation for the reaction shown above which produces a gaseous product.

ii) Use the space provided above to draw the correct number of each molecule present in the reaction flask after the reagents have been converted into products.

Figure 1. Questions 1a and 1b

While the initial focus of the study was the use of student-generated diagrams to probe their understanding of chemical reactions, the analysis of the responses for Question 1 prompted an extension of the study to include a problem where students were required to interpret a submicro diagram and answer questions about the amount of substances present after a reaction had taken place. Question 2, shown in Figure 2, was answered by the 2009 cohort, \((N = 117\) for Test 1 and \(N = 120\) for the June examination). For the purposes of Question 2, each icon represents 1 mole of substance and students would be familiar with this convention. The rationale for repeating the question was based on poor performance for Test 1. Thus Test 1 can be considered as the pre-test while the June examination is equivalent to the post-test for this particular question. Both Questions 1 and 2 depict a reaction mixture in which one of the reagents is present in excess.
Q2a & b The following boxes represent a chemical reaction between \( \text{AB}_2 \) and \( \text{B}_2 \).  

i) Write a balanced equation for the reaction.  
ii) Explain which is the limiting reactant in this reaction.  
iii) Calculate how many moles* of product can be produced when 3 moles \( \text{B}_2 \) react with 5 moles \( \text{AB}_2 \).  
iv) Calculate how many moles of excess reactant remain after the reaction in part (iii) above is complete?  
* The mole is the SI unit for amount of matter.

Figure 2. Questions 2a and 2b

Findings

Question 1

An analysis of students' drawings from their responses to Q1a, Table 1, shows that about 40% of them were able to construct the correct diagram. A further 6.7% could draw the products of the reaction but omitted to include the reagent in excess. There was a variety of incorrect responses. About one fifth of the students drew only the number of product molecules corresponding with the co-efficient in the balanced equation, \( 2\text{H}_2\text{O}, 14.6\% + 5.5\% \) while other diagrams contained drawings of aggregates such as \( \text{H}_2\text{O}_2 \) (12.8%). Two commonly occurring misconceptions were inferred from students' drawings, namely conceptualising the products of a reaction as aggregates e.g. \( \text{H}_2\text{O}_2 \) as well as drawing only the number of products based on the coefficient in the balanced equation, \( 2\text{H}_2\text{O} \). Students conceptualising products as aggregates would arrive at the correct answer if they were solving a numerical problem, thus student-generated diagrams allow insight into this particular misconception.

Table 1. Analysis of responses and representative submicro diagrams for question 1a

<table>
<thead>
<tr>
<th>Students' responses</th>
<th>Submicro drawing</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4\text{H}_2\text{O} + \text{H}_2 )</td>
<td><img src="image1" alt="Image" /></td>
<td>39.6</td>
</tr>
<tr>
<td>( 4\text{H}_2\text{O} ) without excess ( \text{H}_2 )</td>
<td><img src="image2" alt="Image" /></td>
<td>6.7</td>
</tr>
</tbody>
</table>
When analysing the students' drawings of the contents of the container after the reactions depicted in questions 1a and 1b, we considered them to be correct even if the students omitted to draw the reagent in excess. Questions 1a and 1b were essentially the same with respect to depicting the product of a reaction. A comparison of some of the responses is shown in Table 2 below.

**Table 2. Comparison of responses to Questions 1a and 1b.**

<table>
<thead>
<tr>
<th>Submicro drawings of products</th>
<th>Q1a %</th>
<th>Q1b %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct balanced equation</td>
<td>N/A</td>
<td>48.1</td>
</tr>
<tr>
<td>Correct drawings</td>
<td>47.3</td>
<td>67.0</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}_2$ aggregates</td>
<td>12.8</td>
<td>4.3</td>
</tr>
<tr>
<td>$2\text{H}_2\text{O}$; based on co-efficients in balanced equation</td>
<td>20.1</td>
<td>6.1</td>
</tr>
</tbody>
</table>

It is pleasing to note that there was an improvement in students' understanding of stoichiometry as measured by their responses to Question 1b where the number of correct drawings of the product of the reaction increased while the number of students holding misconceptions has decreased. The analysis of student performance on Question 2 is shown in Table 3 below. The correct responses are shown in bold type.

**Table 3. Performance of students on question 2.**

<table>
<thead>
<tr>
<th>Q2a %</th>
<th>Q2b %</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Balanced equation: $2\text{A} \text{B}_2 + \text{B}_2 \rightarrow 2\text{A} \text{B}_3$</td>
<td>11.1</td>
</tr>
</tbody>
</table>
Correct equation but not lowest whole numbers 4.3 3.3
6AB₂ + 5B₂ → 6AB₃ + 2B₂ 29.9 13.3
2AB₂ + 2B₂ → 2AB₃ + B₂ 7.7 6.7
Other unique responses 38.5 24.2
No answer or illegible 8.5 0

ii) Limiting reactant: AB₂
Miscellaneous incorrect responses 23.9 13.3

iii) Moles of product produced: 5
Moles of product 8 i.e.5 + 3 29.9 50.8
Other unique responses 41.8 36.7
No answer or illegible 20.5 10.0

iv) Moles reactant remaining: 0.5
Moles remaining 2 i.e.5 − 3 3.4 15.8
Other unique responses 21.4 15.8
No answer or illegible 53.0 57.5

Once again there was an improvement in performance between the first class test and the June examination. Generating a balanced chemical equation based on a submicro drawing is a difficult concept for novices as shown by the low percentage of students who successfully completed Question 2a(i). Given time and the opportunity to practise, there is an improvement in students' performance. The percentage of correctly balanced equations provided by the 2008 and 2009 cohorts for Questions 1b and 2b(i) respectively is similar and is significantly higher than the 1.6% correct answers reported by Devetak et al. (2004) or Sanger (2005) who reported only 15% correct answers for similar questions. The results show that about one third of students simply counted the icons for Question 2a(i) [6AB₂ + 5B₂ → 6AB₃ + 2B₂], similar to that noted by Devetak et al. (2004). The number of students holding this misconception had dropped to about one in eight by the June examination. A small number of students, (+7%) could balance the equation but included the reagent in excess. The majority of students were able to explain how they identified the limiting reagent which implies that the ability to do so does not depend on being able to balance the chemical equation for the reaction.

In order to answer Question 2(ii) students have understand the meaning of the co-efficients of the balanced equation and how these relate to the amounts of substance available for the reaction. Less than one third of the cohort was successful in answering this question. By the time that students wrote the June examination there was an improvement in performance with about half of students able to determine the amount of product formed in the reaction. One of the misconceptions noted was simply to add the number of moles of reactant. Students' ability to determine the amount of reagent in excess is very poor where once again a significant percentage resorted simply to subtracting the number of moles of reactants. For both Questions 2(iii & iv) students appeared to believe that for a chemical reaction to occur, the reactants must be present in the ratios represented by the balanced chemical equation. The same cohort of students achieved an average mark of 83% for a question in the final examination which required them to perform calculations similar to Questions 2(ii & iii). This confirms previous findings in the literature that students' are able to solve problems using algorithms without the reasoning and processing skills that demonstrate a concomitant conceptual understanding (Nakhleh et al, 1996; Papaphotis & Tsaoparis, 2008).

Discussion and implications for teaching
The student-generated drawings provided insight into students' reasoning and understanding of chemical equations. Evaluation of students' responses to questions requiring interpretation and drawing of submicro diagrams confirmed previous findings reported in the literature (Sanger, 2005). Firstly, some students have misconceptions about the molecular nature and chemical formulae of the products of reactions and secondly, they cannot distinguish between the coefficients and subscripts when
representing chemical formulae e.g. \(2\text{H}_2\text{O} \text{ vs. H}_2\text{O}_2\) (Question 1). While students were generally able to determine the limiting reagent and the amount of product for reactions presented as a set of diagrams (Question 2), a significant number could not generate the balanced equation based on a diagram of the progress of a reaction (Questions 1b and 2).

Evaluation of the submicro drawings revealed that students’ abilities to interpret and construct diagrams of the submicro level as well as their ability to predict the limiting reagent and the correct product of a reaction are, in some cases, independent of their ability to balance chemical equations. There was a significant improvement in performance in drawing and interpreting the submicro diagrams for both cohorts of students. The findings suggest that submicro diagrams are a valuable teaching and assessment tool. Since chemical literacy includes being able to interpret and use chemical diagrams, this skill should be taught and assessed. Teachers cannot assume that students will absorb the information presented to them in submicro diagrams; instead they should guide students to a full understanding of this potentially powerful tool. In this way the diagrams can serve as an explanatory tool providing ways to promote reasoning and thinking (Treagust & Harrison, 1999).

References


