Constraints to the development of first year university chemistry students' mental models of chemical phenomena

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This paper describes the teaching and learning occurring in a first year university chemistry course of a degree in Environmental Biology from the students' perspective. Observations and interviews with students revealed their background knowledge in chemistry, their level of understanding of the concepts being taught and their mental models of chemical phenomena. The constraints to students developing a deeper understanding of chemical phenomena accompanied by better developed mental models, included the students' lack of mental model, their prior knowledge of chemistry, the assessment style of the course, the small number of chemical representations encountered by the student, the large amount of content, the speed with which the chemistry content had to be assimilated by the learner and a lack of motivation by the student to understand chemistry at a deeper level. Despite these constraints, the students did build up a chemical knowledge framework albeit sometimes scant and compartmentalised. The implications of students' experience of learning chemistry are significant and desirably should promote a positive attitude and an appreciation of the value of the subject.

Introduction

This study was designed to investigate the constraints to learning chemical concepts by first year university chemistry students. Aspects of this learning included the students' perceptions of chemical representations, their understanding of chemical concepts and the development of their mental models of chemical phenomena. The influence of the examination and assessment requirements of the course on the students' learning is considered.

The study investigated the personal learning strategies that students have developed in order to learn chemistry and pass the tests. The study is significant in highlighting relevant aspects for improving teaching and learning in chemistry. In this study, the demands of the testing and examination scheme, although fair and reasonable, appeared to conflict with the desired learning outcomes.

Background

Chemistry is an abstract and difficult subject to learn so teachers make use of tangible and visual teaching tools such as diagrammatic representations, verbal and oral descriptions, symbolic representations and physical models to help convey the meaning of new terms and new concepts (Gabel, 1998). Chemical concepts are commonly portrayed at three different levels as described by Johnstone (1982):
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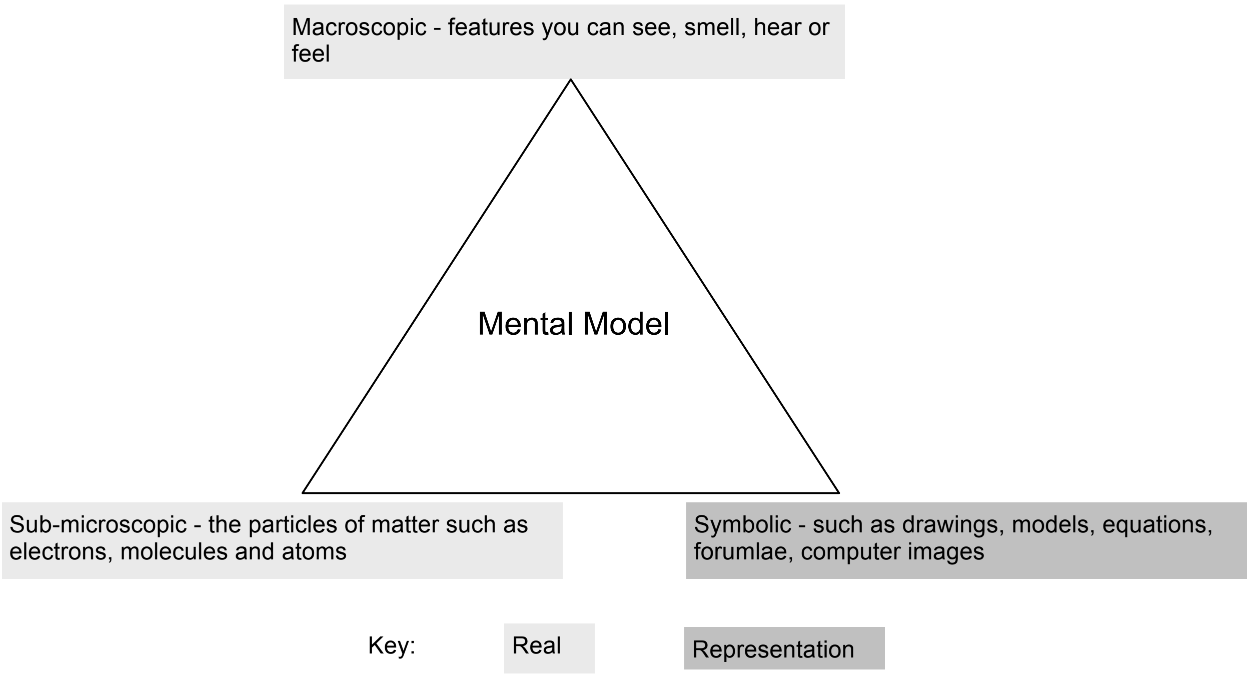
Macroscopic level – the real observable chemical phenomena including references to students' everyday experiences;

Symbolic level – the representation of chemical phenomenon using a variety of media including models, pictures, algebra, and computational forms; and

Sub-microscopic level – the real sub-microscopic particles, which cannot be seen directly, such as electrons, molecules, and atoms.

These three levels are linked and all three contribute to the students' construction of meaning and understanding, which is reflected in their personal mental model of the phenomena.

Figure 1 Chemical descriptions and depictions



The sub-microscopic level cannot be observed, so students must develop a mental model of the behaviour of molecules. This mental model of the sub-microscopic representation is derived from the macroscopic and symbolic representations and it depends on how students understand and interpret chemical data and information. Representations are often misunderstood, with students limiting their view to being replicas of the real thing whereas they can be powerful tools in the development of mental models of chemical phenomena (Grosslight, Unger, Jay & Smith, 1991). Representations link the reality and the theory and in this way are vital to explanations. The ability to transfer from reality to the representation is not always instinctive and must be practised; similarly, the ability to transfer from one type of representation to another is a skill inherent in understanding chemistry. However, students' ability in this regard is often only assumed (Copolo & Hounshell, 1995). The macroscopic observable chemical phenomena are the basis of chemistry, yet explanations usually rely on symbolic representations and/or the sub-microscopic behaviour of particles. The role of these representations are assumed by instructors and consequently are not always clearly defined, despite literature citing common misconceptions arising from their use resulting in erroneous interpretations by students (Andersson, 1990).

Most students who enrol in this first year chemistry course have little previous chemical knowledge, although a small number of students have studied high school chemistry. The course consists of one lecture and a three-hour laboratory session per week. The laboratory tasks are not always in sequence with the theoretical concepts being taught in lectures. A continuous assessment process comprises laboratory work, weekly mastery tests on the lecture content administered by means of a personalised student instruction scheme (PSI), which requires students to gain an 80% pass mark in each test before continuing on to the next test, and an optional final review examination.

Methodology

The aim of the study was to monitor a selected number of students' learning during an introductory chemistry course. Research questions being investigated were:

Q1. How does students' understanding of the macroscopic, sub-microscopic and symbolic levels of representation contribute to developing mental models of chemical concepts?

Q2. What are the constraints to the development of students' mental models?

There were 100 students taking this introductory chemistry course of whom 30 were observed weekly during laboratory sessions. This class of 30 was selected on the basis of the laboratory schedule being convenient for the researcher. This class was generally representative of the overall population of students undertaking the course. Of these 30 students, 15 volunteered to participate in interviews and complete questionnaires. The aspects of age (where available) and gender are reported in Table 1. There are slightly more males represented in the volunteer group than in the population of the whole unit.

Table 1: Comparison of age and gender for the students in the chemistry unit, the laboratory class being observed and the volunteers

Sample	Sample Size	Gender %		Age Profile* %			
Whole Unit	100	35	65	Not available			
Laboratory Group	29	37	63	58	12	15	15
Volunteer Group	15	45	55	61	6	22	11

* Age Profiles

- 1- attended High School last year
- 2-within 2 years of leaving school
- 3- between 2- 5 years of leaving school
- 4- more than 5 years since leaving school

Data collected over a 13-week semester included observations of all student activities in the laboratory; course evaluation by all students doing the course; weekly pen-and-pencil questionnaires completed by the volunteers progressively throughout the semester on such chemical topics as the use of chemical models, moles, solutions and ions, chemical symbols and equilibrium; interviews with the same volunteers in the first four weeks of the course designed to investigate their mental models of chemical compounds and their understanding and preference for a variety of chemical representations; and interviews at the end of the course enquiring about the students' learning strategies, their mental models of chemical compounds, and their understanding of the three levels of chemical representation.

Results

The data analysis identified eight aspects that constrain students' understanding of chemistry. The student-centred aspects include students' appreciation of chemical representations, the lack of any mental model, the students' prior chemical knowledge and a lack of motivation by the student to understand chemistry at a deeper level. The course-centred aspects include the use of chemical representations, the assessment style of the course, the large amount of content and the speed with which the chemistry content had to be assimilated by the learner.

Students' appreciation of chemical representations

Data contributing to answering research question 1 included responses to questionnaires given at the beginning of the semester about the properties and role of models in chemistry. These responses indicated that most students understood the role of models in the process of science and that chemistry is reliant on the use of models and chemical representations. This conclusion is supported by students' comments like: 'models help create an image in your mind', 'models can be of different complexity of the same idea' and 'how a model is made depends on how it is perceived by the human investigator'. The five common attributes of models: models as multiple representations, the accuracy of models, models as explanatory tools, how scientific models are used, and the changing nature of models, were recognised by over 72% of the students surveyed (Treagust, Chittleborough, & Mamiala, in press).

When asked about chemical representations that had been of value to their learning, students comments revealed their appreciation of chemical representations in explanations:

> 'With diagrams oh you know the 'chair' it took me a while to get that - you look at it and say that's like that and then you read about it –see how that is, that's positive and that's negative. If it's there and it is explained in relation to the diagrams it makes it a lot easier.'
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> 'I liked the electron-dot representations they made sense but when it came to organics it was hard to picture them. Benzene was difficult.'

When asked about the meaning of symbolic representations, most students were able to link the symbolic representation to the macroscopic phenomena, for example in a series of acid/base titrations, the results were described graphically and by equations, then interpreted and used to calculate the acid equilibrium constants. Evidence is provided by a student comment in an interview:

> 'I can relate the equation to the experiment, I can understand the equation more now.'

This experiment, the discussion and calculation demonstrated students transferring between the macroscopic and several symbolic levels of representation. However, only a few students believed that they had a sub-microscopic depiction for the particular phenomena. This observation is consistent with the lack of discussion or reference to the students' mental model of the chemical processes during the lecture part of the course. After all, the sub-microscopic level is a result of the students' interpretation of the information they receive. Students depend on information from the text, laboratory work and the lecturer to develop their understanding and personal mental models. Johnstone (1993) proposed that students cannot handle more than two levels in their working memory at one time, and the sub-microscopic level appears to be neglected.

The students' lack of mental model

When asked about their personal 'mental picture' of chemical atoms and compounds, most students drew or described a 'textbook' description of the atom, regurgitating what they had been taught previously. A few students reported that they had no mental picture of an atom in their mind. Mental model is a product of the students interpretation of the images, models, representations they have experienced. 73% of students interviewed provided evidence that their mental model of the sub-microscopic nature of matter had developed throughout the course but they still considered their level of understanding to be primitive. Comments from the interviews revealed some more reflective comments about students 'mental model' including

> 'I do not really have a mental picture of the reaction in my head. I see it in the laboratory and then I understand the equation represents it, but I do not picture it at the atomic level I liked the electron dot formula and I suppose they give me a mental picture to think about.'

> 'If you think of the reaction of photosynthesis- I know the equation; I know what really happens and the equation describes what happens. But I don't picture the little carbon dioxide molecules combining with the water molecules, it just happens; we just know that it does.'

All students interviewed were able to link the macroscopic properties with the symbolic representation primarily as a result of their laboratory experience. However, few students felt they really understood the sub-microscopic nature of chemistry.

Prior chemical knowledge

Students' prior experiences and knowledge in chemistry had a significant influence on their approach, attitude and perception of chemistry. Those students who had studied chemistry in high school held blurred and fragmented mental models as evidenced by reciting memorised definitions such as the symbol for an element, and references to molecular representations such as the electron-dot formula. When asked during the first few weeks of semester to explain how they 'see' the atom in their head many replied, '*I don't*'. Many students had little or no preconceived ideas of the structure of the atom, and their mental models initially were unclear or non-existent.

Towards the end of the course, 27% of students interviewed still held no identifiable mental model for chemical phenomena, stating that they do learn the facts but had no mental picture of the sub-microscopic nature of chemicals. However, 73% of students did provide evidence of the development of their mental models though this was not extensive. The effect of interviewing students and asking them about their mental models and the relationship they perceived between the various levels of representation may have influenced their perceptions and increased their awareness. Many students' reported on the influence of diagrams and drawings of molecular structures on their mental models and some students referred to the importance of these representations in explaining why particular chemical structures looked or existed the way they did. For example, one student described how his understanding of chemical bonds became much clearer when he saw a diagrammatic representation of the electro-negativity of the atoms in a molecule helping him to understand why and how the bond occurred. This linking of representations indicated a more conceptual type of understanding.

A lack of motivation by the student to understand chemistry at a deeper level
Students were highly motivated to learn chemistry to pass the course. Their depth of understanding varied. When asked about the mastery tests

> 'Yeah good, I got them all done, so I didn't do the exam, so I was just basically gonna be a pass, as soon as I got them done, I knew I passed, so I just concentrated on my other units, which I don't know is a good thing or a bad thing'

Do you think you understood it, or did you just rote learn it? 'I think I pretty much rote learned a lot of it.' Can you remember much of it now? 'I don't think I'd be able to get 80% in my tests now, but I think I'd pass.'

The use of chemical representations
Explanations require the communication of ideas and it is proposed that the use of a variety of representations could enhance the learning of chemistry. Kozma and Russell (1997) identified significant differences in the representational competence of experts and novices suggesting that the development of skills in identifying and transforming representations are advantageous to learning chemistry.

Course content and pace
Data contributing to answering research question 2 primarily relates to the structure of the chemistry course, which does impact on the expected and achieved student outcomes. Because of the fast pace at which the course proceeds, most students (93%) used only information from the course notes, laboratory sessions, lecture, and lecturer to learn the content.

During the interviews, students were asked to reflect on their knowledge and provide examples of linking of chemical concepts. Only 13% of the students interviewed were familiar with concept mapping and very few students (20%) had developed an integrated understanding of the chemical concepts that they had been studying. This inability to express links between simple chemical concepts suggests that students have compartmentalised their knowledge structures. Despite this, students had 'learnt' a large amount of chemical content in 13 weeks, and the links between the ideas and their mental models may develop over time now the student has this background information.

Assessment
The course requires the students to demonstrate discipline and perseverance - learning each topic and passing the test - before moving on to the next topic. Consequently, students identified learning strategies and made pragmatic decisions about learning to achieve passing grades in the tests. All students interviewed described rote-learning to be the primary method of preparation for tests. Indeed, this can be attributed to the assessment scheme, the volume of material that the students have to learn and the speed at which it is covered. The eleven topic tests are mainly of an algorithmic style and do not require conceptual understanding.

The most common strategies were: practicing problems, highlighting and memorising notes in the text, studying worked solutions and getting help with mistakes after doing topic tests. Only 20% of the students interviewed obtained help from peers and there was no formal provision for collaborative discussions as part of the teaching program. Unfortunately, the assessment process reinforced the memorisation of facts and algorithmic understanding (Nakhleh, Lowrey & Mitchell, 1996).

Conclusion

Rote learning can have a valuable role in chemistry (Battino, 1992); however, the process of learning should not be marginalised by the need for assessment. Although the teaching strategies in the laboratory and the lecture did encourage meaningful learning, the primary focus on algorithmic style test items directed students towards a rote-learning regime and did not foster the development of students' mental model of the chemical phenomena. Similarly, the volume of chemical content and the speed at which students must digest it also constrains students' understanding. The task of thinking about chemical phenomena at a sub-microscopic level is aided by the use of macroscopic and symbolic representations when used in an integrated way.

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