Educational research

The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation

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Abstract: A 15-item two-tier multiple-choice diagnostic instrument was developed to evaluate secondary students' ability to describe and explain seven types of chemical reactions using macroscopic, submicroscopic and symbolic representations. A mixed qualitative and quantitative case study was conducted over four years involving 787 Years 9 and 10 students (15 to 16 years old). The instrument was administered to sixty-five Year 9 students after nine months of instruction to evaluate their use of multiple levels of representation. Analysis of the students' responses demonstrated acceptable reliability of the instrument, a wide range of difficulty indices and acceptable discrimination indices for 12 of the items. The teaching program proved to be successful in that in most instances students were able to describe and explain the observed changes in terms of the atoms, molecules and ions that were involved in the chemical reactions using appropriate symbols, formulas, and chemical and ionic equations. Nevertheless, despite the emphasis on multiple levels of representation during instruction, 14 conceptions were identified that indicated confusion between macroscopic and submicroscopic representations, a tendency to extrapolate bulk macroscopic properties of substances to the submicroscopic level, and limited understanding of the symbolic representational system. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 293-307.]

Keywords: chemical reactions, macroscopic, submicroscopic and symbolic representations, student conceptions

Introduction

The theoretical basis of this study is a constructivist approach that is grounded in the belief that what a learner already knows is a major factor in determining the outcomes of learning (Ausubel, 1968). Learners are provided with opportunities to develop new understandings with the teacher acting as a facilitator of learning rather than as a transmitter of knowledge. The complex and abstract nature of chemistry makes the study of the subject difficult for students (Ben-Zvi et al., 1987, 1988; Johnstone, 1991, 1993; Nakhleh, 1992; Gabel, 1998, 1999; Treagust and Chittleborough, 2001). As a result, students tend to hold particular idiosyncratic views about scientific phenomena and concepts that they bring with them to science lessons. These conceptions that students develop (referred to as student conceptions) are the result of several factors, such as their sensory experiences and the influence of their cultural background, peers, mass media as well as classroom instruction (Duit and Treagust, 1995). Very often, the conceptions that students develop about the behaviour of matter tend to differ from the views that are held by the scientific community (Osborne et al., 1983). It is likely that students are satisfied with their own conceptions as a result of viewing material that is presented by their teachers or textbooks "*through the lenses of their preinstructional conceptions*" (Duit and Treagust, 1995; p. 47).

The unique conceptions about natural phenomena that are held by students are often resistant to instruction. One reason for this resistance to change is the tendency for these conceptions to become firmly entrenched in students' minds as coherent but mistaken conceptual structures (Driver and Easley, 1978), especially when students' conceptions are deeply rooted in their everyday life experiences. As a result, when the new concepts do not make sense to them, students tend to adhere firmly to their own views (Treagust et al., 1996). Consequently, it is beneficial to identify students' conceptions so that appropriate strategies may be formulated that will challenge their understandings in order to help them develop more scientifically acceptable views of science concepts.

One of the reasons for the difficulties that students experience in understanding the nature of matter is related to the multiple *levels of representation* that are used in chemistry instruction to describe and explain chemical phenomena (Yarroch, 1985; Andersson, 1986; Ben-Zvi et al., 1986; Gabel et al., 1987; Johnstone, 1991, 1993; Nakhleh and Krajcik, 1994). For the purpose of this study the three representations relevant to understanding of chemistry concepts are: (1) *macroscopic representations* that describe bulk properties of tangible and visible phenomena in the everyday experiences of learners when observing changes in the properties of matter (e.g. colour changes, pH of aqueous solutions, and the formation of gases and precipitates in chemical reactions), (2) *submicroscopic (or molecular) representations* that provide explanations at the particulate level in which matter is described as being composed of atoms, molecules and ions, and (3) *symbolic* (or *iconic*) *representations* that involve the use of chemical symbols, formulas and equations, as well as molecular structure drawings, diagrams, models and computer animations to symbolise matter.

The acquisition of knowledge by students without a clear understanding may be attributed to the confusion caused in having to deal simultaneously with the macroscopic, submicroscopic and symbolic worlds of chemistry. From observations of the macroscopic changes that are observed, students have to explain these changes at the particulate level. The particulate level in turn is represented by symbols and formulas. As a result of having to deal with these three levels of representation simultaneously, learners generally experience difficulty in explaining chemical reactions (Gabel, 1998).

In order to help students develop conceptual understanding of chemical representations, several studies conducted over the past few decades (Ben-Zvi et al., 1986; Keig and Rubba, 1993; Kozma and Russell, 1997) indicate that students experience difficulty in understanding the submicroscopic and symbolic representations because these representations are abstract and cannot be experienced (Ben-Zvi et al., 1986, 1988; Griffiths and Preston, 1992). Students' thinking, on the other hand, is heavily influenced by sensory information that they are able to experience. Also, students often are not able to translate one given representation into another due to their limited conceptual knowledge and poor visual-spatial ability (Seddon and Eniaiyeju, 1986; Keig and Rubba, 1993).

Similarly, research also has shown that many high school teachers do not integrate the three representations in their teaching but move between representational levels without highlighting their inter-connectedness (Gabel, 1999). As a result, students are often unable to see the linkages between the three levels of representation although they may know the chemistry at the three levels. For improved conceptual understanding, it is important to help students see the connections between the three levels of representation (Gabel, 1999). A convenient way of studying students' ability to make use of multiple levels of representation when describing and explaining chemical phenomena involves the use of two-tier multiple-choice diagnostic instruments. The advantages and successful use of these instruments in several studies are discussed next.

As a result of the limitations of the clinical interview method that is time consuming and not convenient for use by classroom teachers, science education researchers have recognized the need for short paper and pencil tests for obtaining data from large whole class or samples of students. These tests included multiple-choice items that initially evaluated only content knowledge without considering the reasoning behind students' choices of responses (Duncan and Johnstone, 1973). As an improvement of this methodology, Tamir (1971) proposed the use of multiple-choice test items that included responses with known student alternative conceptions, and that also required students to justify their choice of option by giving a reason. Tamir (1989) found the use of justifications when answering multiple-choice test items to be a sensitive and effective way of assessing meaningful learning among students and addresses, to some extent, the limitations of traditional multiple-choice test items.

The positive outcomes of findings related to students' justifications to test items led to the development of two-tier multiple-choice diagnostic tests specifically for the purpose of identifying students' alternative conceptions in limited and clearly defined content areas. These short paper and pencil tests are convenient to administer and not time consuming to mark. Treagust (1988, 1995) has provided useful guidelines for the development of these instruments specifically for the purpose of identifying students' alternative conceptions about various concepts. The first tier of the items consists of a content question, while the second tier elicits a reasoning response. The need to select a justification in these multiple-choice items affords a sensitive and effective way of assessing meaningful learning among students and also serves as an effective diagnostic tool (Tamir, 1989). To date, several diagnostic tests have been developed and are described in the literature (Haslam and Treagust, 1987; Peterson et al., 1989; Odom and Barrow, 1995; Tan and Treagust, 1999; Tan et al., 2002; Chou and Chiu, 2004; Wang, 2004; Treagust, 2006).

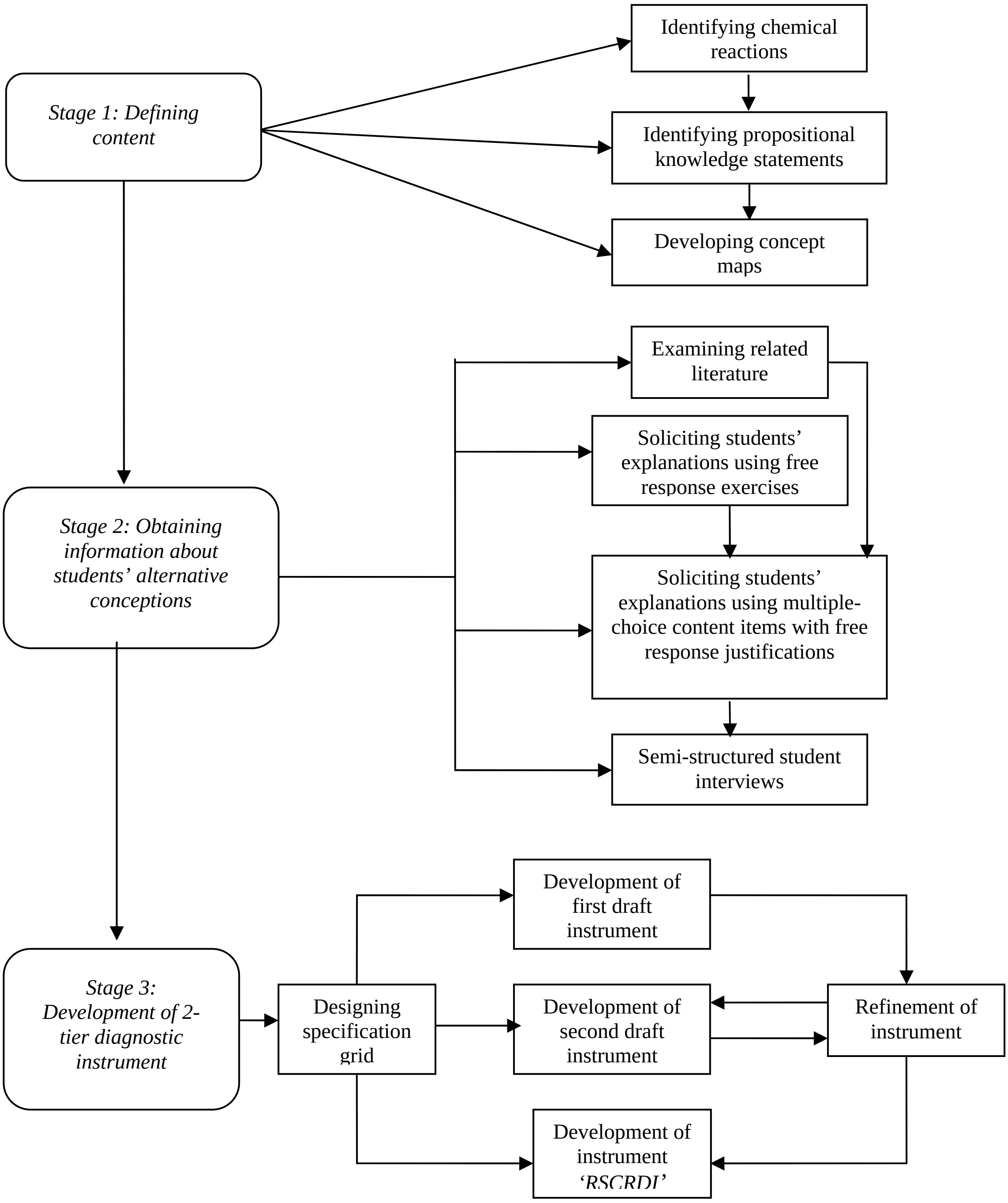
The purpose of the study

The observed changes during chemical reactions include colour changes, gas evolution, 'disappearance' of solid reactants, and formation of precipitates. The purpose of this study was to develop a two-tier multiple-choice diagnostic instrument in order to assess the ease with which 15 to 16 year old students in Years 9 and 10 were able to explain the observed changes in chemical reactions (macroscopic representations) in terms of atoms, molecules and ions (submicroscopic representations) as well as with the use of chemical symbols, formulas and equations (symbolic representations). Seven types of chemical reactions that were frequently encountered in their chemistry course were included in this study.

Methods and procedures

This case study, incorporating both qualitative and quantitative methods, involved a convenience sample (Merriam, 1998) of 787 Years 9 and 10 students aged 15 to16 years old from a Singapore secondary school who were selected during the course of the study over a period of four years. The instrument was developed in three stages (see Figure 1) using the procedure proposed by Treagust (1995). Stage 1 involved defining the content area of the study. Stage 2 involved identifying students' conceptions when describing and explaining chemical reactions using multiple levels of representation (based on responses solicited from two groups consisting 515 and 95 students). Stage 3 involved several steps in the designing of test items and the validation of the final version of the two-tier multiple-choice diagnostic instrument (based on responses solicited from 177 students).

Figure 1. Scheme of development of the Representational Systems and Chemical Reactions Diagnostic Instrument (RSCRDI) based on Treagust (1988, 1995)



Stage 1 – Defining the content area of the study

Based on inspection of the chemistry syllabus, seven types of chemical reactions that were frequently encountered by Years 9 and 10 students (15 to 16 years old) were identified. All seven types were introduced to the students in the chemistry scheme of work for Year 9 and were included in three major topics, namely, the properties of acids and bases, the metal reactivity series and qualitative inorganic analysis. These seven types of chemical reactions were: combustion of metals, reactions between dilute acids and reactive metals, neutralisation reactions between strong acids and strong alkalis, neutralisation reactions between dilute acids and metal oxides, chemical reactions between dilute acids and metal carbonates, ionic

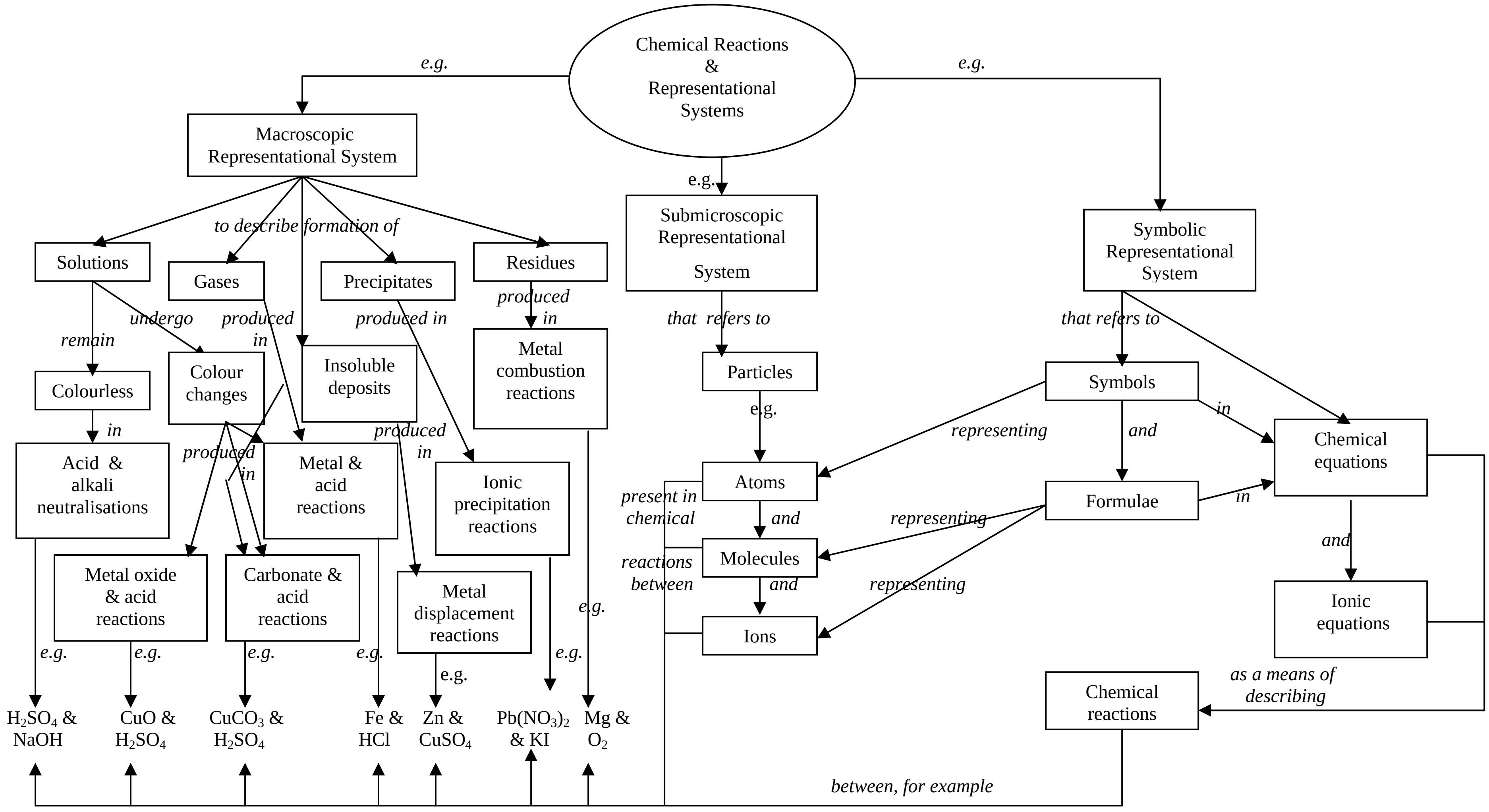


Figure 2. Concept map of representational systems for describing chemical reactions

precipitation reactions, and metal-ion displacement reactions. The content area was defined using thirty-nine propositional statements that were encapsulated in a concept map (Chandrasegaran, 2004) in Figure 2. As a reliability check, in order to ensure that the underlying concepts and propositional knowledge statements referred to the same topic area, seven concept maps were developed, one for each of the chemical reactions that were included in this study. All the concept maps were validated by two colleagues of the first author who were also involved in teaching chemistry in Years 9 and 10, as well as by two tertiary level science education professors and a chemistry lecturer.

Stage 2 – Identifying students' conceptions when describing and explaining chemical reactions using multiple levels of representation

An important aspect of this study involved identifying their conceptions when students described and explained the seven chemical reactions using multiple levels of representation. Apart from reviewing the research literature, students' conceptions were identified from their written responses in 11 exercises that included semi-structured and free response questions. These exercises were administered by the first author and six of his teaching colleagues to 515 Years 9 and 10 students. The chemical reactions that were referred to in these exercises were each demonstrated to the students prior to their attempting the exercises. An example of one of these exercises for the chemical reaction between aqueous solutions of lead(II) nitrate and potassium iodide is reproduced in Figure 3.

Figure 3. Worksheet VI: Reaction between aqueous solutions of lead(II) nitrate and potassium iodide.

You have seen what happens when a colourless aqueous solution of potassium iodide is added from a dropping pipette, with shaking, to some aqueous lead(II) nitrate in a test-tube, until no further change occurs.
A bright yellow precipitate is instantly produced.
On allowing to stand, the yellow precipitate settles to the bottom, with a colourless solution above it.
The changes that occur can be represented by the chemical equation,
$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$

Question 1: Name the yellow precipitate produced.
Question 2: What does the chemical equation tell you about the changes that have occurred?
Using your knowledge about atoms, molecules and ions, answer Questions 3 - 8.
Question 3: Name the particles present in aqueous lead(II) nitrate.
Question 4: Name the particles present in aqueous potassium iodide.
Question 5: Name the particles present in the yellow precipitate.
Question 6: Name the particles present in the colourless solution finally produced.
Question 7: Name the particles that have remained unchanged in solution.
Question 8: Deduce the ionic equation for the changes that have occurred.

When the experiment is repeated using colourless aqueous solutions of lead(II) ethanoate, $(CH_3COO)_2Pb$, and sodium iodide, a yellow precipitate and a colourless solution are again produced.
Question 9: Write a balanced chemical equation for the changes that occur, indicating all state symbols.
Question 10: Write a balanced ionic equation for the changes that occur, indicating all state symbols.
Question 11: On allowing the yellow precipitate to settle, what colourless solution would you expect to see above the precipitate?

Subsequently, 33 multiple-choice items were developed consisting of two, three or four responses, one of which was the expected answer. The distractors in the items were based on student conceptions that were identified from the research literature as well as from students' responses to the 11 written exercises referred to in stage 2. The 33 multiple-choice items were content-validated by two science education professors and a chemistry senior lecturer. For each item a space was provided for students to supply a reason for the response that they had selected (Treagust, 1995).

The 33 items were trialled by administering to ninety-five students in three Year 10 classes that were taught by the first author. Following analysis of more than 1,000 justifications that were provided by the students, semi-structured interviews were conducted with seventeen students. These students were selected because of ambiguities in several justifications that were provided by them. A list of students' conceptions was then compiled from their responses to the written exercises and the justifications that were provided to the 33 multiple-choice items. Several of these student conceptions were subsequently used in the construction of the two-tier multiple-choice diagnostic instrument discussed in the next section.

Stage 3 – Development and **validation** *of the two-tier multiple-choice diagnostic instrument*

After studying the justifications that were provided by the students to the multiple-choice items in the previous section, 33 two-tier multiple-choice items were developed. The second tier elicited a reasoning response (for the selection made in the first tier) that had to be chosen from two, three or four responses. One of the responses was the expected reason while the distractors consisted of incorrect reasons as well as scientifically unacceptable conceptions held by students. The item options were chosen from students' responses to the written exercises in stage 2, the research literature and from the first author's teaching experience.

The items were validated by a teaching colleague of the first author and two science education professors. The 33 items constituted the first draft of the two-tier diagnostic instrument. After two successive trials (involving 177 Year 10 students), the final version of the instrument, the *Representational Systems and Chemical Reactions Diagnostic Instrument* (RSCRDI) consisting of 15 items was developed incorporating 30 student conceptions that were identified in stage 2 of the study. In deciding on the final 15 items, consideration was given to items that elicited a wide range of responses, apart from ensuring that all the chemical reactions were adequately included in the instrument. The draft and final versions of the instruments were developed based on a specification grid designed to ensure that the instruments satisfactorily incorporated the propositional knowledge statements relating to the chemical reactions involved. Examples of two items in the RSCRDI are found in Figure 4. A complete version of the RSCRDI may be obtained from the first author.

Figure 4. Examples of two-tier multiple-choice items from the RSCRDI.

Item 10

Dilute sulfuric acid is added to some black copper(II) oxide powder and warmed. The copper(II) oxide disappears producing a blue solution.
Why is a blue solution produced?

A The copper(II) oxide dissolves in the acid producing a blue solution.
B Copper(II) oxide reacts with dilute sulfuric acid, producing a soluble salt, copper(II) sulfate.
C Copper(II) oxide is anhydrous. When the acid is added the copper(II) oxide becomes hydrated and turns blue.

*The **reason** for my answer is:*

1 The ions in copper(II) sulfate are soluble in water.
2 Cu^{2+} ions have been produced in the chemical reaction.
3 Hydrated salts contain molecules of water of crystallisation.
4 Cu^{2+} ions originally present in insoluble copper(II) oxide are now present in soluble copper(II) sulfate.

Item 14

When powdered zinc is added to blue aqueous copper(II) sulfate and the mixture shaken, the blue colour of the solution gradually fades and it becomes colourless. At the same time a reddish-brown deposit is produced.
The chemical equation for the reaction that occurs is,

$$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s),$$

while the ionic equation is, $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$.

Why did the solution finally become colourless?

A Copper has formed a precipitate.
B Zinc is more reactive than copper(II) sulfate.
C The copper(II) sulfate has completely reacted.
D Zinc has dissolved, just like sugar dissolves in water.

*The **reason** for my answer is:*

1 Zinc ions are soluble in water.
2 Zinc loses electrons more readily than copper.
3 Soluble, blue Cu^{2+} ions have formed insoluble, reddish-brown copper atoms.
4 In aqueous solution Cu^{2+} ions produce a blue solution, while Zn^{2+} ions produce a colourless solution.

Evaluation of the RSCRDI

The RSCRDI was evaluated for its usefulness in assessing students’ proficiency in using multiple levels of representation. The instrument was administered to a sample of sixty-five students from two Year 9 classes after nine months of instruction during which time they were introduced to the seven chemical reactions relevant to this study. The two classes that were selected for this study were the only two Year 9 classes (out of a total of 10 classes involved in the learning of chemistry) that were taught by the first author.

Statistical Analysis of RSCRDI

The responses of the sixty-five students to the 15 items in the RSCRDI were analysed using a SPSS statistics software program. The students obtained a mean score of 11 out of 15. The answer to an item was considered to be correct if both content and reason parts were correctly answered. The reliability of the instrument was established by a Cronbach alpha coefficient of 0.65 for the 65 cases and 15 items. This value is acceptable as it is greater than the threshold value of 0.5 for multiple-choice items quoted by Nunally (1978). The difficulty indices of the items ranged from 0.35 to 0.94 providing a wide range of difficulty in the items. The discrimination indices ranged from 0.35 to 0.59 for 12 of the 15 items. A discrimination index greater than 0.3 is considered acceptable (Lien, 1971). Three of the items that did not meet this criterion would require further refinement.

Item analysis of two-tier test items in RSCRDI

Analysis of students' responses revealed that of the 30 student conceptions that were incorporated in the items in the RSCRDI, 14 were held by at least 10% of the Year 9 students to whom the instrument was administered after nine months of instruction using a specially designed program that provided opportunities for students to perform the chemical reactions themselves, and to discuss in small groups the submicroscopic and symbolic representations used to describe and explain the observed macroscopic changes. Despite efforts to facilitate the use of multiple levels of representation during instruction, it was not surprising that several student conceptions were resistant to instruction. The 14 student conceptions and the percentage of students who held these conceptions are summarized in Table 1. Students' responses to the items in which these conceptions emerged are discussed next.

Table 1. Several non-scientific conceptions held by students (N = 65) when using multiple levels of representation to describe and explain chemical reactions.

Chemical reactions	Item no.	Students' conceptions	Percentage of students
Burning of magnesium	2	Mg^{2+} ions are present in magnesium ribbon. (mac, **sub, sym**)	14
		The symbol for the element magnesium is Mg^{2+}. (mac, sub, sym)	14
Iron powder and dilute HCl	3	Atoms of iron and chlorine become green when they combine together. (mac, sub)	15
Dilute acid and aqueous alkali	8	Na^+ ions and NO_3^- ions react in aqueous solution to produce sodium nitrate. (**mac**, sub, sym)	20
	9	The ionic equation for the reaction between a dilute acid and aqueous alkali depends on the stoichiometry of the chemical equation. (mac, **sym**)	11
Metal oxides and dilute acid	10	Cu^{2+} ions exist only in aqueous solution, not in the solid and liquid states. (mac, sub, sym)	25
	11	Iron(III) oxide dissolves in dilute hydrochloric acid. (mac)	15
		Individual Fe^{2+} ions in aqueous solution are green (mac, sub, sym)	15
Aqueous lead(II) nitrate and aqueous solutions of iodides	12	The ionic equation for the reaction of aqueous potassium iodide with lead(II) nitrate displays all the ions present in the reactants and products. (sub, sym)	11
	13	The ionic equations for the reactions of aqueous lead(II) nitrate with aqueous potassium iodide and with aqueous sodium iodide depend on the stoichiometry of the two chemical equations. (mac, **sym**)	12
Zinc and aqueous copper(II) sulfate	14	Cu^{2+} ions in aqueous solution are blue. (mac, sub, sym)	31
		Copper atoms are reddish-brown. (mac, sub)	31
		Copper atoms are insoluble in water. (mac, sub, sym)	31
		A reddish-brown precipitate of copper is produced when zinc is added to aqueous copper(II) sulfate. (mac)	11

Note: The abbreviations mac, sub and sym denote the macroscopic, submicroscopic and symbolic representations

The burning of magnesium ribbon

Item 2 in the RSCRDI referred to the symbol for magnesium that is present in magnesium ribbon. A relatively high proportion of students (75%) made the correct selection indicating that the symbol for magnesium in magnesium ribbon is 'Mg' because the particles in magnesium ribbon are neutral atoms. These students were able to represent magnesium using a symbolic representation in terms of the neutral magnesium atoms that are present (submicroscopic representation).

Fourteen percent of students, however, held the conceptions that Mg^{2+} ions (submicroscopic and symbolic representations) were present in magnesium ribbon (macroscopic representation) and that the metal magnesium had a charge of +2 (symbolic representation). The suggestion that magnesium ribbon consists of Mg^{2+} ions may have been associated with the explanation for the structure of metals in which the presence of metallic bonding is regarded as resulting from the electrostatic attraction between positive nuclei of metal atoms and the ‘sea’ of mobile valence electrons. However, the suggestion that magnesium (instead of the particles in magnesium) has a charge of +2 indicates confusion between the macroscopic and submicroscopic levels of representation.

Chemical reactions of dilute acids

Item 3 in the RSCRDI involved explaining the formation of a light-green solution when dilute hydrochloric acid was added to iron powder. Only 66% of the students made the correct selection, suggesting that the colour of the solution could be attributed to the formation of iron(II) chloride in aqueous solution (macroscopic representation). The students justified their choice by explaining that the green colour was due to the presence of Fe^{2+} ions in aqueous solution (submicroscopic and symbolic representations). Fifteen percent of the students, however, held the conception that chlorine and iron atoms turned green when they reacted to produce iron(II) chloride in aqueous solution.

In Item 4 students were required to explain how hydrogen gas was produced in the chemical reaction between dilute hydrochloric acid and iron powder in Item 3. Forty-three percent of students incorrectly suggested that acids produce hydrogen when they react with *all* metals, although they correctly explained that in this reaction iron displaces hydrogen ions (submicroscopic level) from aqueous solution because iron is more reactive than hydrogen (macroscopic level). However, the incorrect factual statement was not included as a student conception in Table 1 as the statement does not involve students’ facility with the use of multiple levels of representation.

Item 8 in the RSCRDI involved the chemical reaction between dilute nitric acid and aqueous sodium hydroxide. The net change that occurred was the removal of equal numbers of H^+ ions and OH^- ions to produce water molecules (submicroscopic and symbolic representations). Although 91% of the students suggested that the resulting solution was neutral (macroscopic representation), only 71% of the students indicated understanding of the macroscopic change as involving a reaction between equal numbers of H^+ ions and OH^- ions in aqueous solution at the submicroscopic level of representation. The reference to an equal number of the two ions indicated additional understanding at the symbolic level of representation about the stoichiometry of the chemical reaction between nitric acid and sodium hydroxide. Twenty percent of the students, however, held the conception that Na^+ ions had reacted with NO_3^- ions (submicroscopic and symbolic representations) to produce aqueous sodium nitrate (macroscopic representation). This inappropriate explanation may have been the result of students knowing that, at the macroscopic level of representation, sodium nitrate was a product of the chemical reaction.

Item 9 of the RSCRDI required students to compare the ionic equation for the reaction in Item 8 with that when dilute hydrochloric acid reacted with aqueous potassium hydroxide. A high proportion of students (88%) correctly suggested that the macroscopic change produced by either pair of dilute acid and alkali would be similar as the net change at the submicroscopic representational level involved the same ions (H^+ and OH^- ions). Despite the similar net reaction that occurred in both cases involving the removal of equal numbers of H^+ ions and OH^- ions to produce water molecules (submicroscopic and symbolic representations), 11% of the students failed to see the common feature in the two chemical reactions at the symbolic level represented by the identical ionic equation. They suggested that the ionic equations for the two neutralisation reactions would depend on the reaction stoichiometries of the two chemical reactions.

Item 10 in the RSCRDI required an explanation for the formation of a blue solution as a result of the chemical reaction between dilute sulfuric acid and copper(II) oxide. Despite 91% of the students selecting the correct content choice that soluble copper(II) sulfate had been produced (macroscopic representation), only 66% selected the correct reason. These students indicated the correct view that the formation of the blue aqueous solution of copper(II) sulfate could be explained in terms of the Cu^{2+} ions that were now present in aqueous solution (submicroscopic and symbolic representations). Twenty-five percent of the students, however, held the conception that Cu^{2+} ions could only be present in aqueous solution, but not in the solid state.

Item 11 in the RSCRDI involved the reaction of iron(III) oxide powder with dilute hydrochloric acid and with dilute sulfuric acid. A high proportion of students (72%) could identify the similarity in the chemical reactions between iron(III) oxide and the two acids. These students agreed that the macroscopic change in both chemical reactions involved the same interaction between H^+ ions and O^{2-} ions (submicroscopic and symbolic representations). However, 15% of the students held the conception that the solid iron(III) oxide had dissolved in the dilute acid (macroscopic representation) and that *green* Fe^{2+} *ions* (macroscopic, submicroscopic and symbolic representations) were present in aqueous solution after the chemical reaction.

Chemical reaction between an aqueous solution of lead(II) nitrate and aqueous solutions of iodides

Item 12 in the RSCRDI involved deducing the ionic equation for the ionic precipitation of lead(II) iodide in the reaction between aqueous solutions of lead(II) nitrate and potassium iodide. A very high proportion of students (91%) was able to select the correct ionic equation. Yet, only 75% of students displayed understanding of the reason for not including the 'spectator ions' K^+ and NO_3^- in the ionic equation. Eleven percent of the students held the conception that the ionic equation included all the ions that were present in the reactants and products (submicroscopic and symbolic representations), displaying lack of understanding of the net chemical change involving merely the removal of Pb^{2+} ions and I^- ions from aqueous solution.

Item 13 in the RSCRDI involved the chemical reaction between aqueous solutions of lead(II) nitrate and sodium iodide. Students had to decide whether or not the ionic equation for this chemical reaction was the same as that in Item 12 when aqueous potassium iodide was used instead of sodium iodide. Seventy-four percent of the students displayed understanding of the significance of the balanced chemical equation at the symbolic level of representation and the involvement of only the Pb^{2+} ions and I^- ions at the submicroscopic level represented by the ionic equation. However, 12% of the students held the conception that the ionic equation would be different for the two chemical reactions as the number of ions present in aqueous solution had an influence on the ionic equation, even though there was no difference in the two reaction stoichiometries in this case.

Displacement of copper(II) ions from aqueous copper(II) sulfate by metals

Item 14 in the RSCRDI required an explanation for the change in colour of the solution from blue to colourless and the formation of a copper coating resulting from the chemical reaction between zinc powder and aqueous copper(II) sulfate. Only 40% of the students were successful in answering this item. These students believed that the blue solution turned colourless because the copper(II) sulfate had reacted completely (macroscopic representation). They also agreed with the explanation that the blue solution that was due to the presence of Cu^{2+} ions, had turned colourless because the Cu^{2+} ions were no longer present in aqueous solution. The solution now contained Zn^{2+} ions resulting in the formation of a colourless solution (submicroscopic and symbolic representations).

On the other hand, 31% of the students indicated an extrapolation of bulk macroscopic properties of matter to the submicroscopic level of representation in their reasoning. Their choice of response indicated their belief that individual Cu^{2+} ions were blue in aqueous solution. At the same time they implied that copper atoms were reddish-brown and were insoluble in water. Also, 11% of the students showed ignorance of the definition of the term precipitation, by suggesting that a reddish-brown precipitate of copper was produced as a result of the chemical reaction. (The term *precipitation* is used in the chemistry course to refer to the formation of an insoluble salt that is produced by mixing two or more aqueous solutions together).

Conclusions and implications for teaching and research

Despite the limitations of this study that involved students from a single school, the findings about the efficacy of the diagnostic instrument make a significant, albeit limited, contribution to our knowledge about evaluating high school students' proficiency in using multiple levels of representation when describing and explaining chemical reactions. Analysis of students' responses to the items in the RSCRDI has shown, that despite efforts during instruction to facilitate students' use of multiple levels of representation, several student conceptions still persisted among the students who were involved in this study. Administration of the RSCRDI to evaluate students' understandings about the use of multiple levels of representation will provide useful information to teachers in the planning of classroom instruction by incorporating strategies that challenge students' conceptions in order to engender more meaningful understandings.

The resistance to change of students' conceptions is not unexpected as these conceptions are deep-rooted and often "*difficult to shift, and can offer a serious barrier to effective teaching*" (Tytler, 2002; p. 15). For example, students in this study demonstrated confusion between macroscopic and submicroscopic representations when they suggested that the metal magnesium (instead of the particles in magnesium) has a charge of +2 (please see the earlier section on the burning of magnesium ribbon for the likely reason for this confusion), and that iron and chlorine atoms turned green when iron powder reacted with dilute hydrochloric acid.

In other instances students displayed a tendency to extrapolate the bulk macroscopic properties of matter to the submicroscopic level by suggesting for example that insoluble, reddish-brown atoms of copper were produced in the displacement reaction between zinc powder and aqueous copper(II) sulfate. They also attributed the fading of the blue colour of the solution to the removal of individual *blue* Cu^{2+} *ions*, as a result of extrapolating the blue colour of the bulk solution to the submicroscopic level of representation.

Students were also relatively uncertain about the significance of symbolic representations, especially with regard to ionic equations. This weakness was evident in their understanding of the reactions between different pairs of strong acids and strong alkalis, different metal oxides and different dilute acids and the ionic precipitation of lead(II) iodide on adding aqueous lead(II) nitrate to aqueous solutions of different iodides. Despite a special teaching program to address these issues, it was not evident to several students that the changes at the submicroscopic level were essentially the same for each pair of reactants, and that as a result the ionic equation was identical in each case.

On the positive side, analysis of students' responses on the diagnostic test indicated, in several instances, students' ability to use multiple levels of representation to describe and explain the chemical reactions. For example, in the reaction between a strong acid and strong alkali, most students were able to relate the changes at the macroscopic level (production of a solution neutral to litmus indicator) to the changes at the submicroscopic and symbolic levels of representation (removal of equal numbers of H^+ ions and OH^- ions from aqueous solution). In another example involving the reactions of aqueous lead(II) nitrate with aqueous solutions of potassium iodide and sodium iodide, respectively, students were generally able to associate the same observed change at the macroscopic level (the production of a yellow precipitate of lead(II) iodide) in both reactions to the same change at the submicroscopic level using symbolic representations (removal of Pb^{2+} and I^- ions represented by the same ionic equation).

Several implications for classroom practice are evident from the results of this study. First, the findings about the efficacy of the RSCRDI in assessing students' proficiency in using multiple levels of representation could contribute to the professional development of chemistry teachers. The instrument could be used prior to or after classroom instruction to identify student conceptions when they use multiple levels of representation. Based on the findings, teachers could plan and institute relevant measures to reduce the incidence of their students' misunderstandings in the use of multiple levels of representation.

Second, there is a need to place greater emphasis on the correct use of multiple levels of representation when describing and explaining chemical phenomena during classroom instruction. All too often teachers take it for granted that students are able to switch back and forth between levels of representation with ease. This study has shown that this was far from the case when students described and explained chemical reactions. The findings of this study could facilitate teachers in their planning and implementation of relevant measures to reduce the incidence of their students' misunderstandings in the use of multiple levels of representation.

Third, students should be provided with opportunities to perform the chemical reactions themselves and discuss with their peers the observed changes in terms of the particles involved. Following this, discussion of the multiple levels of representation associated with the corresponding chemical equation for the reaction should be emphasized. The performing of additional similar chemical reactions by students themselves or as demonstrations by the teacher could help further consolidate students' conceptions. For example, using several metal oxides to react with different dilute acids will help illustrate the similarities in the chemical reactions although different salts are produced. Once students are aware of the similarities in the chemical reactions, deducing the ionic equations for the reactions would become a more meaningful endeavour than the common practice of 'cancelling out' the 'spectator ions' from the overall balanced chemical equation.

Fourth, classroom instruction may be organised in a manner that takes into account student conceptions similar to the ones that have been identified in this study. When directly confronted with conceptions that students realise are not scientifically acceptable and through discussions with the teacher and with peers in small groups, students may be led to arrive at more fruitful understandings of the changes that occur in chemical reactions.

Finally, the use of multi-media software and computer animations that illustrate the changes that the atoms, ions and molecules undergo during chemical reactions can further reinforce the relationship between the observed changes and the changes at the particulate level (Ardac and Akaygun, 2005, 2006; Tasker and Dalton, 2006). In addition, several commercially produced software packages and materials from the internet, after prudent evaluation to ascertain their suitability, provide additional resources for teachers. (See for example, Interactive Courseware for Chemistry, Acids and Bases, and Qualitative Analysis on http://www.cool-science.net).

For successful implementation of the suggestions discussed above, curriculum planners have the responsibility to consider the formulation of syllabuses that take into account research findings in science education that promote student learning with understanding rather than accumulation of knowledge that is rote-learned. In the absence of such considerations, efforts to engender meaningful learning during classroom instruction at all levels are unlikely to be realised.

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