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Understanding rate of acid reactions: Comparison between pre-service teachers and Grade 10 students

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Abstract

A two-tier multiple choice diagnostic instrument on the stoichiometry and rate of acid reaction was administered to 611 Grade 10 students and 171 pre-service teachers. The results showed that the Grade 10 students and pre-service teachers had alternative conceptions related to the properties of different acids affecting their rates of reaction, and the particles in the resulting mixtures at the end of the reactions. The study stresses the importance of identifying and clarifying the pre-service teachers' understanding of the concepts that they will teach as this may have consequences on their future students' learning of chemistry.

(96 words)

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Introduction

Chemistry is a difficult subject for students to learn, even up to the tertiary levels (Nieswandt, 2001; Taber, 2000), because explanations of chemical phenomena not only involve abstract concepts and models, they can also be communicated and perceived in three different but inter-related ways such as experiences, models and visualizations (Talanquer, 2011). For example, when excess dilute hydrochloric acid is added to a piece of magnesium ribbon, students can see bubbles forming on the metal, and the metal becomes smaller and smaller until it disappears. If sensors are used to monitor the reaction, they can see changes in pH, temperature and/or pressure in digital and/or graphical forms, or if a gas syringe is used to collect the hydrogen gas, changes in volume can be observed. These are the students' experiences of the chemical phenomena. At the secondary level, the teacher can provide explanations of the reaction using models of varying sophistication. For example, the teacher can simply state that a metal reacts with an acid to produce a salt and hydrogen, or also point out that a redox reaction has occurred where the metal donates electrons to the hydrogen ions which come into contact with it to form hydrogen gas. In secondary chemistry (Grades 9 and 10) in Singapore, the simpler term, 'hydrogen ions', is used instead of 'hydroxonium ions'. Deeper understanding of acid reactions will require knowledge of acid-base models and concepts such as acid strength, neutralization, pH, dissociation and chemical equilibrium, and research has shown that students have difficulty understanding these concepts (Baddock & Bucat, 2008; Carr, 1984; Lin & Chiu, 2007; McClary & Talanquer, 2011; Nakhleh & Krajcik, 1994; Ross & Munby, 1991; Schmidt, 1997; Sheppard, 2006; Wilson, 1998). As the concepts involved in acid reactions are numerous and intertwined, if students have problems understanding one concept, they will have difficulty learning other related concepts as well (McClary & Talanquer, 2011; McDermott, 1988; Ross & Munby, 1991; Sheppard, 2006).

To represent the experience and the explanations of magnesium reacting with hydrochloric acid, the teacher could use chemical symbols and equations such as:

$$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$$

$$Mg(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$$

The teacher could also show the students animations of the particles interacting during the reaction to help them understand the phenomenon and the models used to explain it. Thus, students have to coordinate the information from their sensory experiences of the phenomena and the explanations, as well as the models and visualisations provided by the teacher or textbook, to form a coherent understanding of the reaction of magnesium and hydrochloric acid.

If the students are studying the rate of acid reactions, they need to be able to interpret or compare graphs depicting amount of product or reactant over time, a common task in secondary school kinetics in Singapore. In addition to understanding the conventions of graphical representations, students also need to understand the chemistry involved, for example, the characteristics of the reactants, reactions and products, the stoichiometry involved and the factors affecting the rates of reactions as these would determine the amounts of reactants used up or products formed, and how fast they are formed (Tan, Treagust, Chandrasegaran, & Mocerino, 2010). For example, if students are comparing the reactions of sulfuric, hydrochloric and ethanoic acids with similar masses of powdered magnesium at the same temperature, they need to bear in mind which reactant is the limiting reagent as this will impact on the amount of hydrogen gas and salt formed, as well as the concentration and dissociation of the acids as these will impact on the concentration of hydrogen ions reacting with the metal, and hence the rate of reaction. Understanding the graphs involved may be challenging as studies have shown that students have difficulty with the concepts involved in chemical kinetics (Cakmakci, Leach, & Donnelly, 2006; van Driel, 2002), stoichiometry (Chandrasegaran, Treagust, Waldrip, & Chandrasegaran, 2009; Gauchon & Meheut, 2007) and have problems interpreting graphs (Leinhardt, Zaslavsky, & Stein, 1990; Testa, Monroy, & Sassi, 2002).

Teachers, too, may have similar alternative conceptions and difficulties as their students (Abell, 2007), for example, in the areas of chemical equilibrium (Quilez-Pardo & Solaz-Portoles, 1995) and chemical kinetics (Justi, 1997). It is important to help teachers to identify their own alternative conceptions and difficulties, and address them because their own conceptions may impact on how they teach their students (de Jong, Veal, & van Driel, 2002; Crawford, 2007) and give rise to poor learning of concepts by their students.

Purpose

The study sought to compare pre-service teachers' and Grade 10 students' understanding of the concepts involved in the stoichiometry and rate of acid reactions and to highlight the significance of the nature of the alternative conceptions. A two-tier multiple choice diagnostic instrument, the Acid Reactions Diagnostic Instrument, was used in the study, and it was developed from an open-ended version used in an earlier study (Tan et al., 2010).

Instrument

The Acid Reactions Diagnostic Instrument (ARDI) (see Appendix), was developed through several stages (Treagust, 1995) which included the clarification of the curricular content knowledge, interviews and open-ended versions of the instrument (Tan et al., 2010) before the version used in this study was finalized. It consists of six single-tier and eight two-tier multiple-choice items. Two-tier multiple-choice items require the participants to select two options, the answer and the reason for the answer. Only if both options are correctly selected is the two-tier multiple-choice question considered correctly answered (Peterson, Treagust, & Garnett, 1989). There are four reaction scenarios, each consisting of three questions, in the instrument. The first item in each scenario requires the participants to select a graph which best describes the two reactions in the scenario. The following two items require students to explain the amount of gases formed and the rate of the two reactions in the scenario. The last two items (items 13 and 14) were designed to clarify the participants' understanding of excess and limiting reagents as it was difficult to decide if the participants gave wrong answers in the earlier items due to their misreading of the questions or if they actually had difficulties with the concepts of excess and limiting reagents. Six chemistry teachers reviewed the items in the ARDI and agreed that the content assessed by the ARDI is in line with the national secondary chemistry syllabus and taught in schools.

Method and procedures

The study involved 611 Grade 10 students from six Singapore schools in 2010 and 171 graduate pre-service teachers from a teacher education institution in Singapore over the period 2010 and 2011. It was part of a larger collaborative research project focusing on the development of diagnostic instruments to identify student conceptual difficulties in chemistry and received human ethics research approval (SMEC-47-09).

Convenience sampling was used in the study. Six schools in Singapore which were approached by the first author agreed to participate in the study. The Grade 10 students in the schools were chosen by the schools and the ARDI was administered to the students after they were taught the topics of Bonding, Acids, Bases and Salts, Stoichiometry and Reaction

Kinetics, all of which were required in the secondary chemistry syllabus. Only the overall analysis of the results of the students in a particular school was reported back to the school with an offer of discussions with teachers on students' difficulties and how to address these; none of the offers to the six schools was taken up. The graduate pre-service teachers in the sample were from a teacher education institution in Singapore. They answered the ARDI as part of a series of lessons designed to highlight difficult concepts in secondary chemistry. It was one of the three diagnostic instruments used in the lessons, the other two being the Qualitative Analysis Diagnostic Instrument (Tan, Goh, Chia, & Treagust, 2002) and Taber's (1997) instrument on ionic bonding. The pre-service teachers were informed in advance to read up the relevant Grade 10 chemistry material before attempting the diagnostic instruments and had also seen demonstrations of the reaction of magnesium with similar concentrations of sulfuric acid, hydrochloric acid and ethanoic acid in a session on the instructional use of demonstrations and the Predict-Observe-Explain strategy. The pre-service teachers' results were used, in subsequent sessions, to compare with secondary students' results reported in the literature or collected by the first author to facilitate discussions on the prevalence and 'longevity' of alternative conceptions (Taber & Tan, 2011), and how to address them when teaching in school.

Graduate pre-service teachers aspiring to teach in secondary schools are assigned two teaching subjects. Ninety-five pre-service teachers were assigned secondary chemistry as their first teaching subject (CS1) and these teachers would have at least undergraduate degrees in science (majoring in chemistry), material science, material engineering or chemical engineering. The remaining 76 pre-service teachers were assigned secondary chemistry as their second teaching subject (CS2). They would have studied at least up to Grade 12 chemistry; many of them have science degrees but majored in mathematics, life sciences or physics, while the rest are usually engineering graduates. The content of the chemistry pedagogy courses and the way the courses were conducted were similar for both groups of pre-service teachers as both groups could be assigned to teach secondary chemistry in school. The main difference between the two groups is that the CS1 pre-service teachers can be assigned to teach high school (Grades 11 and 12) chemistry as well.

Results

The answer sheets were scanned using an optical mark reader, and the results were analysed using IBM SPSS Statistics version 19 (SPSS Inc, 2010). Questions 1, 4, 7, 10, 13 and 14 are one-tier questions, and contain 5 to 8 options. The reason for the use of options (A-E) and (1-5) is that the answer sheet was designed for two-tier tests in which respondents chose an answer (A-E) and a reason for the answer (1-5). Thus, to accommodate up to 10 options, (A-E) and (1-5) of each row of answers had to be utilised. There should not be any errors in recording responses as options (A-E) and (1-5) have corresponding circles to be shaded on the answer sheet. There were respondents who provided 'two responses' for the single-tier questions. However, these were not taken into account when the results of these questions were analysed.

Some test statistics are given in Table 1 and the distribution of the total scores is illustrated in Figure 1. The pre-service teachers did reasonably well, the mean total score of the CS1 and CS2 groups being 11.09 and 10.18 (out of a maximum of 14), respectively, compared to the mean total score of 8.26 of the Grade 10 students. However, it is rather disconcerting that 9.5% and 21.1% of the pre-service teachers in the CS1 and CS2 groups, respectively, scored 7 marks or less in the test (Grade 10: 42.4%). A one-way analysis of variance (ANOVA) showed that there was a statistically significant difference between mean total scores of the three groups ($p<0.001$). A post hoc pairwise multiple comparisons analysis (Dunnett's T3) was conducted and it showed that there was no statistically significant difference between the mean total scores of the two groups of pre-service teachers ($p=0.144$). As expected, both groups of pre-service teachers' mean total scores were significantly different statistically compared to that of the Grade 10 students ($p<0.001$ for both comparisons). However, any comparison needs to be taken with caution because of the different numbers of Grade 10 students (n=611) and pre-service teachers (n[CS1]=95, n[CS2]=76) involved. The pre-service teachers' and Grade 10 students' correct responses to the four reaction scenarios are given in Table 2. As expected, the percentages of the pre-service teachers and Grade 10 students who choose the correct graph in each reaction scenario (CS1, 64–87%; CS2, 62–76%; Grade 10, 52–80%) are generally higher than those who chose the correct graphs and explanations for the volumes of gas formed and the rates of the reaction involved (CS1, 59–85%; CS2, 50–72%; Grade 10, 40–69%). Cronbach alpha values for the instrument administrated to the three groups range between 0.73 to 0.82 indicating acceptable to good internal consistency.

(Insert Tables 1 and 2, and Figure 1 about here)

Alternative conceptions

Table 3 summarises the alternative conceptions of the two groups of pre-service teachers and Grade 10 students. Alternative conceptions are considered significant if they exist in at least 10% of the sample (Tan et al., 2002). In general, the effect of the same concentration of different acids on the initial rate of reactions posed difficulties to both groups of pre-service teachers and Grade 10 students. As mentioned earlier, items 13 and 14 were included in the instrument to clarify the respondents' understanding of excess and limiting reagents. However, in addition to performing this task, the two items also revealed students' ideas of the existence of the various particles in solution.

(Insert Table 3 about here)

The initial rates of reaction of different acids of the same concentration are equal

In items 1, 7 and 10, more than 10% of the respondents in the three groups chose graphs which indicated that the correct volumes of gas liberated but incorrect initial rates of reaction; they thought that initial rate of reaction of the same concentrations of different acids were the same (see Figure 2). The hydrochloric/sulfuric acid pair in item 1 (Option 2: CS1, 27%; CS2, 28%; Grade 10, 20%) and item 10 (Option B: CS1, 19%; CS2, 25%; Grade 10, 25%) seemed to pose more difficulty than the hydrochloric/ethanoic acid pair in item 7 (Option 2: CS1, 12%; CS2, 18%; Grade 10, 19%). Cross-tabulation (see Table 4) showed that about half of the respondents were consistent in their choices in item 1 and item 10 (CS1, 12%; CS2, 17%; Grade 10, 9%) but fewer respondents were consistent in items 1 and 7 (CS1, 3%; CS2, 8%; Grade 10, 10%) and in all three items (CS1, 3%; CS2, 5%; Grade 10, 5%).

(Insert Figure 2 and Table 4 about here)

In items 3, 9 and 12, the respondents had to explain the rates of reaction represented by the graphs in items 1, 7 and 10. It could be seen again in Table 3 that the percentage of students explaining that the rates of reactions were the same because the acids were of the same concentration was higher in items 3 (Option B1: CS1, 12%; CS2, 14%; Grade 10, 23%) and 12 (Option B2: CS1, 14%; CS2, 17%; Grade 10, 27%) which involved the hydrochloric/sulfuric acid pair than item 9 which involved the hydrochloric/ethanoic acid pair (Option B2: CS1, <10%; CS2, <10%; Grade 10, 11%). More than half of the pre-service teachers and about half the Grade 10 students were consistent in their ‘same concentration same rate of reaction' reasoning (see Table 4) in items 3 and 12 (CS1, 9%; CS2, 12%; Grade 10, 13%); however, consistency in this reasoning across items 3, 9 and 12 is low (CS1, 0%; CS2, 1%; Grade 10, 6%).

The next step taken was to cross-tabulate respondents' answers within the same reaction scenarios to determine if the 'same concentration same rate of reaction' reasoning was consistent across the respondents' graphical and text description choices. The results show that the consistency in the respondents' choices is higher again for items 1 and 3, and 10 and 12 involving the hydrochloric/sulfuric acid pair than for items 7 and 9 involving the hydrochloric/ethanoic acid pair (see Table 4). This is expected as, in general, a higher proportion of respondents exhibited the 'same concentration same rate of reaction' reasoning in the reaction scenarios involving the hydrochloric/sulfuric acid pair.

Other alternative conceptions related to the initial rates of reaction

Other incidences of significant alternative conceptions related to the initial rates of reaction are few and involved only one of the three groups of respondents (see Table 3). For example, in item 3 (B2), 10% of the CS1 pre-service teachers indicated that the initial rates of reaction of powdered copper(II) carbonate with hydrochloric acid and sulfuric acid, respectively, are the same because both acids were in excess, while 12% of the CS2 pre-service teachers pointed out in item 12 (B1) that the initial rates of reaction of the same two acids with powdered magnesium were the same because the acids were strong acids. In item 9 (B3), 14% of the Grade 10 students indicated that the initial rates of reaction of powdered marble with hydrochloric and ethanoic acids were the same because the strength of the acids did not affect their rates of reaction.

Ignoring excess/limiting reagents

A number of Grade 10 students (11%) seemed to ignore that the 0.5 mol dm^{-3} and 1 mol dm^{-3} hydrochloric acids were in excess, and chose option C4 in item 5 stating that the reaction of powdered marble with 1 mol dm^{-3} hydrochloric acid will liberate more carbon dioxide because it contains more hydrogen ions (see Table 3). Cross-tabulation with item 14 showed that only 12 students (2%) chose options A, B, C or D in item 14 which indicated that the metal was in excess (see Figure 3) when it was stated in the item that the acid was in excess. Similarly, another 11% of the Grade 10 students ignored that the fact the acids were the limiting reagent in item 11 (B2) but cross-tabulation with item 13 showed that only 11 students (2%) chose options E, 1, 2, 3, 4 or 5 indicating that the acid was in excess when it was stated that the metal was in excess. The consistency of the Grade 10 students' choices is only 2% in item 5 (C4) and item 11 (B1). The pre-service teachers did not have any significant problem with excess/limiting reagents.

(Insert Figure 3 about here)

Ionic molecules in solution and electrically unbalanced solution

The use of items 13 and 14 to determine the respondents' understanding of excess and limiting reagents in terms of the particles present in solution when the reactions were completed indicated that the respondents had little problems with excess and limiting reagents, but revealed the existence of the 'ionic molecules in solution' and 'electrically unbalanced solution' alternative conceptions. A significant number of respondents chose option B in item 13 (CS1, 17%; CS2, 24%; Grade 10, 52%) and option E in item 14 (CS1, 16%; CS2, 26%; Grade 10, 50%) which showed the ionic salt, MgY_2, existing as a molecule (see Figure 4), and this thinking was consistent across the two items (CS1, 16%; CS2, 21%; Grade 10, 45%). Item 14 (3) also indicated that a number of respondents (CS1, 15%; CS2, 14%; Grade 10, 10%) ignored the charges of the oppositely charged particles were unbalanced; insufficient Y^- ions were present to balance the positive Mg^{2+} and H^+ ions in the diagram (see Figure 5).

(Insert Figures 4 and 5 about here)

Discussion

From Table 2, it can be seen that a large majority of pre-service teachers and Grade 10 students who chose the correct graphical representations of the reactions in each reaction scenario chose the correct textual descriptions of the graphs in first tier options of the second and third items in the same reaction scenario (CS1, 93-99%; CS2, 87-100%; Grade 10, 92–96%) as well as provided correct explanations for the volumes of gas formed and the rates of reaction (first and second tier options in the second and third items in the same reaction scenario) (CS1, 85-98%; CS2, 72-100%; Grade 10, 77-94%). This indicates the importance of exposing students to both graphical as well as textual/verbal descriptions when teaching rates of reaction as they serve complementary roles in helping students to construct deeper understanding of the concepts involved (Ainsworth, 1999); the graphs can illustrate textual/verbal descriptions of reaction changes due to changes in the variables involved or of the comparison of two different reactions, facilitating understanding of the textual/verbal descriptions. Reaction scenario 2 which involved different concentrations of only one acid seemed to cause lesser problems than the other reaction scenarios which involved two different acids as more participants chose the correct graph and explanations for this scenario compared to the other three reaction scenarios. This is expected as the complexity of determining how the characteristics of different acids affect the rate of reaction and volume of gas formed does not come into play in the scenario, making comparisons easier.

Similar to the earlier study (Tan et al., 2010), a significant number of respondents chose graphs which indicate equal initial rates of reactions for the hydrochloric/sulfuric acid pair in items 1 (20-28%) and 10 (19-25%) and the hydrochloric/ethanoic acid pair in item 7 (12-19%) (see Figure 2). The main reason given by the respondents was that both acids had the same concentration (Q3 (B1): 12-23%; Q12 (B2) 14-27%; Q9 (B2): 3-11%). In Grade 9 and 10 chemistry, students learn that concentration is one of the factors which affect the rate of reaction and since the concentration of the different acids are the same in reaction scenarios 1, 3 and 4, it is easy to understand why Grade 10 students chose the incorrect 'same concentration same rate of reaction' option. They might have taken what was taught at face value and did not understand that the characteristics of the reactants, reaction itself, products formed and stoichiometry involved needed to be considered in greater detail. For example, marble chips will react with hydrochloric acid to liberate carbon dioxide until the limiting reagent is used up. However, the reaction of marble chips and sulfuric acid (not included in the ARDI) will slow down and stop producing carbon dioxide soon after the reaction starts due to the formation of a coating of sparingly soluble calcium sulfate on the surface of the marble chips, preventing further reaction between the acid and the calcium carbonate. Sulfuric acid will react with a metal or carbonate faster than hydrochloric acid of the same volume and concentration provided a *soluble sulfate* is formed. It is a diprotic acid and although its second ionisation is low, the hydrogensulfate ions will dissociate further to generate more hydrogen ions as they are used up, unlike hydrochloric acid where the hydrogen ions cannot be replenished, causing a drop in the concentration of hydrogen ions and slowing down its rate of reaction. Thus, graph 1 in item 1 and graph D in item 10 are the best options.

$$H_2SO_4\,(aq) + H_2O\,(l) \rightarrow H_3O^+\,(aq) + HSO_4^-\,(aq),\ pKa = -\,3.0$$

$$HSO_4^-\,(aq) + H_2O\,(l) \rightarrow H_3O^+\,(aq) + SO_4^{2-}\,(aq),\ pK_a = 1.9$$

It is rather surprising that the pre-service teachers also exhibited the ‘same concentration same rate of reaction’ alternative conception even after learning chemistry at more advanced levels, albeit at a lower percentage compared to the Grade 10 students, and quite a number exhibited this thinking consistently in items involving the hydrochloric/sulfuric acid pair in in reaction scenarios 1 and 4 (see Tables 3 and 4). These pre-service teachers still focused on the concentration of the acids rather than the concentration of the hydrogen ions present in the acids (Tan et al., 2010), highlighting the insidious nature (Taber & Tan, 2011) of this alternative conception. Thus, there is a need to emphasise the ionic equations and the stoichiometry of the reaction when discussing the reactions of acids to focus attention that the reacting species is the hydrogen ion rather than the acid per se. Other minor incorrect reasons that the respondents offered to explain why the hydrochloric/sulfuric acid pair and the hydrochloric/ethanoic acid pair had the same initial rate of reaction included both acids were in excess (Q3 (B2): CS1, 10%), both acids were strong acids (Q12 (B1, CS2, 12%) and the strength of an acid did not affect its rate of reaction (Q9 (B3), Grade 10, 14%). Merely watching the reactions of the same concentration and volume of the three acids with magnesium apparently did not make much of an impression; the demonstrations or practical activities need to be supported with illustrations of the particles and their interactions at the sub-microscopic level to represent the reaction in multiple and complementary ways to help students (and pre-service teachers) construct deeper understanding of the process (Ainsworth, 1999). Computer animations or relevant diagrams can be used to show what excess reagent and strength of acids mean at the sub-microscopic level and how these affect reactions. For example, even if an acid is in excess, it is still the number of hydrogen ions in the immediate vicinity of the metal and colliding with metal that is responsible for the initial reaction rate, and this number of hydrogen ions is determined by the concentration and dissociation of the acid rather than the excess hydrogen ions which are spread throughout the mixture.

The respondents, in general, had little difficulty with the concepts of excess and limiting reagents per se, as indicated by their answers in items 14 and 13, even though they made incorrect choices in items 5 and 11, respectively. However, items 13 and 14 established that the respondents had problems with the representation of '$MgY_2(aq)$', with about 17% of the CS1 group, 25% of the CS2 group and 51% of the Grade 10 students incorrectly believing that MgY_2 exists as an 'ionic molecules' (Taber, 1997; Tan & Treagust, 1999) in solution, and the consistency of their alternative conception ranged from 16% (CS1) to 45% (Grade 10). Devetak and Glazar (2010) also found that students in their study had problems representing soluble ionic substances in solution, drawing aqueous potassium bromide as ion-pair molecules. Taber (1997) and Tan and Treagust (1999) argue that the teaching of ionic bonding at the secondary level, focussing on the transfer of electrons to form discrete units of the ionic compound, encourages students to adopt this molecular framework (Taber, 1997) and this is another tenacious alternative conception, defying the impact of additional years of chemical education. Item 14 also revealed the 'electrically unbalanced solution' choice which a number of respondents (10-15%) made. These respondents might have focussed only on the hydrogen ions in the depiction of excess acid, forgetting that an equal number of counter-ions (Y^-) would have to be present as well. The learning of the ions present in solution (and in the molten state) can be facilitated, again, by computer animations or the use of relevant diagrams to give students a picture of how solutions of ionic compounds (and molten ionic compounds) would look like; hopefully, this would minimise students and pre-service teachers persisting with the molecular framework.

Conclusion

This study indicates that the pre-service teachers and Grade 10 students did not have difficulty with the concepts of excess and limiting reagents per se although a number of Grade 10 students seemed to ignore the excess and limiting reagents when determining the amounts of products formed in reactions. However, many pre-service teachers and Grade 10 students had alternative conceptions related to rates of reaction of different acids such as the initial rates of reaction of the same concentration of acids of different proticity or strengths are equal. They also had problems describing how the various substances exist in resulting mixtures at the end of the reaction, for example, they indicated that 'ionic molecules' exist in solution or chose options which show electrically unbalanced solutions. The most likely cause of these difficulties is the lack of understanding of the sub-microscopic representations of the properties and reactions of acids (Tan et al., 2010). Thus, there is a pressing need for illustrations of the entities and process at the sub-microscopic level to be included in chemistry lessons to foster complementary learning and deeper understanding (Ainsworth, 1999). The study also highlights the need to help pre-service teachers to identify tenacious alternative conceptions that they may have and clarify their understanding of the chemistry concepts that they will be teaching as what they think about these concepts may affect their classroom teaching and the learning of their future students.

(4820 words)

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Appendix 1. The Acid Reactions Diagnostic Instrument

(submitted as a separate document to prevent formatting issues with the diagrams in the instrument)

Figure 1. Distribution of total scores of the two groups of pre-service teachers and the Grade 10 students

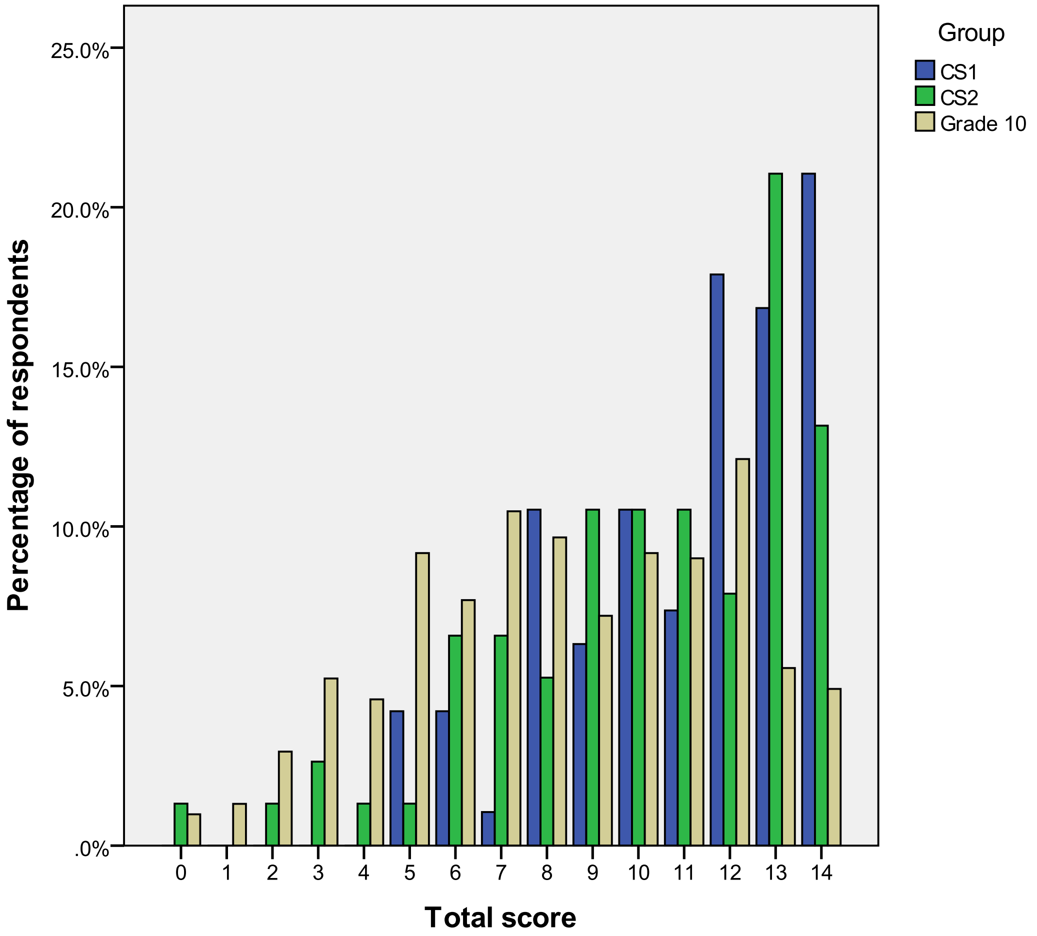
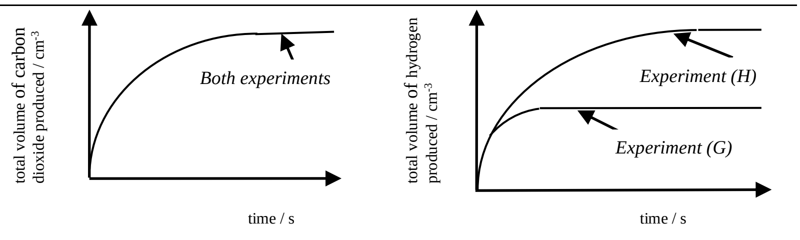


Figure 2. Options indicating 'same concentration same rate of reaction' alternative conception



Option 2 in items 1 and 7 Option B in item 10

Figure 3. Options indicating excess metal in reaction mixture in item 14

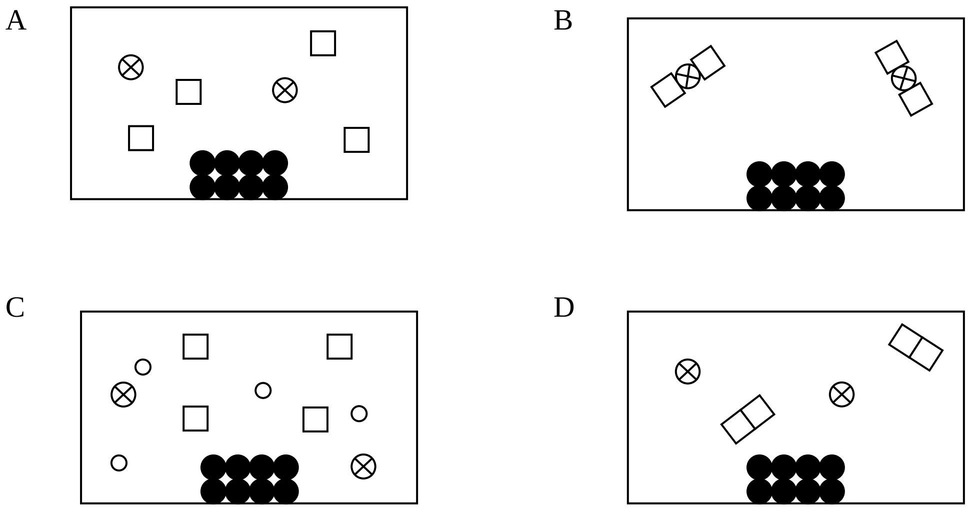
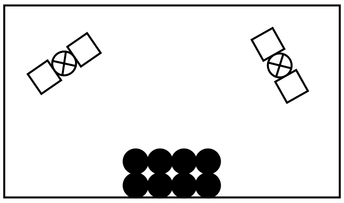
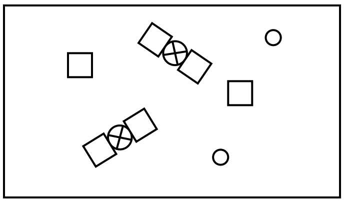


Figure 4. Options indicating ‘ionic molecules’ in solution



Option B in item 13



Option E in item 14

Figure 5. Option indicating an electrically unbalanced solution in item 14

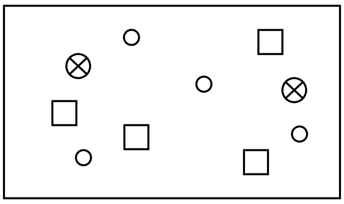


Table 1. Test statistics for the administration of the ARDI to pre-service teachers and Grade 10 students

	CS1	CS2	Grade 10
No. of cases	95	76	611
Cronbach alpha reliability	0.732	0.816	0.820
Mean (Standard deviation)	11.09 (2.62)	10.18 (3.28)	8.26 (3.45)
Median / Mode	12.00 / 14	11.00 / 13	8.00 / 12
Minimum / Maximum	5 / 14	0 / 14	0 / 14
Number (Percentage) of respondents whose total scores are 7 and below	9 (9.5)	16 (21.1)	259 (42.4)

Notes:
CS1 represents pre-service teachers with chemistry as their first teaching subject
CS2 represents pre-service teachers with chemistry as their second teaching subject

Table 2. Frequency of correct responses to the items in the four reaction scenarios (% in parentheses)

Reaction Scenarios	Reaction kinetics	CS1 (n = 95)	CS2 (n = 76)	Grade 10 (n = 612)
1	Excess 1M-HCl and 1M- H_2SO_4 with $CuCO_3$:			
	Correct response to Q1	61 (64)	48 (63)	319 (52)
	Correct responses to Q1, Q2 (1st tier) & Q3 (1st tier)	57 (60)	48 (63)	305 (50)
	Correct responses to Q1, Q2 (both tiers) & Q3 (both tiers)	56 (59)	48 (63)	300 (49)
2	Excess 1M-HCl and 0.5M-HCl with $CaCO_3$:			
	Correct response to Q4	83 (87)	56 (74)	492 (80)
	Correct responses to Q4, Q5 (1st tier) & Q6 (1st tier)	82 (86)	56 (74)	465 (76)
	Correct responses to Q4, Q5 (both tiers) & Q6 (both tiers)	81 (85)	55 (72)	424 (69)
3	Excess 1M-HCl and 1M-CH_3COOH with $CaCO_3$:			
	Correct response to Q7	72 (76)	58 (76)	319 (52)
	Correct responses to Q7, Q8 (1st tier) & Q9 (1st tier)	69 (73)	57 (75)	294 (48)
	Correct responses to Q7, Q8 (both tiers) & Q9 (both tiers)	61 (64)	42 (55)	247 (40)
4	Excess magnesium with 1M-HCl and 1M-H_2SO_4:			
	Correct response to Q10	69 (73)	47 (62)	396 (66)
	Correct responses to Q10, Q11 (1st tier) & Q12 (1st tier)	64 (67)	41 (54)	372 (62)
	Correct responses to Q10, Q11 (both tiers) & Q12 (both tiers)	59 (62)	38 (50)	368 (61)

Table 3. Significant alternative conceptions of the pre-service teachers and the Grade 10 students

Alternative conception	Choice combination	Percentage of respondents with the alternative conception		
		CS1 (n=95)	CS2 (n=76)	Grade 10 (n=611)
The initial rates of reactions of different acids of the same concentration are equal (graph with the correct volumes of gas liberated are correct)	Q1 (2)	27	28	20
	Q7 (2)	12	18	19
	Q10 (B)	19	25	25
The two initial rates of reaction are equal because both acids have the same concentration (text)	Q3 (B1)	12	14	23
	Q9 (B2)	~	~	11
	Q12 (B2)	14	17	27
The two initial rates of reaction are equal because both acids are in excess	Q3 (B2)	10	~	~
The two initial rates of reaction are equal because the strength of the acid does not affect its rate of reaction	Q9 (B3)	~	~	14
The two initial rates of reaction are equal because both the acids are strong acids	Q12 (B1)	~	12	~
Ignore excess/limiting reagents	Q5 (C4)	~	~	11
	Q11 (B2)	~	~	11
Ionic 'molecule' in solution	Q13 (B)	17	24	52
	Q14 (E)	16	26	50
Electrically unbalanced solution	Q14 (3)	15	14	10

Note: ~ represents a figure which is less than 10%

Table 4. Consistency of pre-service teachers' and Grade 10 students' alternative conceptions

Alternative conception	Percentage of respondents with the alternative conception		
	CS1 (n=95)	CS2 (n=76)	Grade 10 (n=611)
The initial rates of reactions of different acids of the same concentration are equal. Volumes of gas liberated are correct			
Graph			
Q1 (2) & Q7 (2)	3	8	10
Q1 (2) & Q10 (B)	12	17	9
Q1 (2), Q7 (2) & Q10 (B)	3	5	5
Text			
Q3 (B1) & Q12 (B2)	9	12	13
Q3 (B1), Q9 (B2) & Q12 (B2)	0	1	6
Graph and text			
Q1 (2) & Q3 (B1)	7	12	16
Q7 (2) & Q9 (B2)	3	7	7
Q10 (B) & Q12 (B2)	11	14	15
Ignore excess/limiting reagents			
Q5 (C4) & Q11 (B2)	0	1	2
Ionic 'molecule' in solution			
Q13 (B) & Q14 (E)	16	21	45