Levels of students' understanding in the explanation tier of conceptual tests of electrochemistry

The students were categorized into five levels of understanding regarding their explanations in the conceptual tests. Prior to the involvement of 5E inquiry experiments and the model kit of electrochemistry, the percentages of students in the very poor, poor, fair, good, and excellent categories were 48.37, 21.24, 20.26, 8.50, and 1.63, respectively, for the oxidation–reduction reactions topic, and 65.29, 13.73, 13.53, 6.67, and 0.78, respectively, for the galvanic cell topic (Table 4). After the intervention, the percentages of students in the very poor, poor, fair, good, and excellent categories were 6.54, 7.52, 14.38, 16.67, and 54.90, respectively, for the oxidation–reduction reactions topic, and 11.96, 11.57, 13.53, 15.29, and 47.65, respectively, for the galvanic cell topic. Notice that the percentages of students decreased in the less understanding categories but increased in the more correct categories.

Examples of students' responses in conceptual test

Consider the students' responses in the explanation tier for Question 1 in the conceptual test of electrochemistry (see also Fig. 3). Please note that if students did not supply any response in the explanation tier, they were awarded 0.00 point automatically. Some students chose the correct choice (C) but supplied incorrect explanation such as 'Fe(s) is a reducing agent because it gained electrons, while Cu^{2+}(aq) is an oxidizing agent because it lost electrons'. This case was awarded 0.25 point in the explanation tier because it was considered as misunderstood. Some students chose incorrect choice (A) and provided almost correct explanation such as 'Fe^{2+}(aq) is a reducing agent because its oxidation number increased from 0 to +2, while Cu^{2+}(aq) is an oxidizing agent because its' oxidation number decreased from +2 to 0'. This case was awarded 0.75 point in the explanation tier. Although the explanation about decreasing and increasing oxidation numbers was correct, the consideration of oxidation number of Fe(s) and Fe^{2+}(aq) was switched from the right to left hand-side of the chemical equation (incorrect). Some students chose incorrect choice (B) but provided correct explanation such as 'Cu^{2+}(aq) is a reducing agent because it gained electrons and became Cu(s), while Fe(s) is an oxidizing agent because it lost electrons and became Fe^{2+}(aq)'. This case was awarded 1.00 point in the explanation tier because the explanation about gaining and losing electrons of reducing and oxidizing agents was correct.

Table 4 Percentages of students in 5 levels of understanding in the explanation tier of conceptual tests (n = 34)

Conceptual test (no. of items)	Percentage of students (%)				
	Very poor	Poor	Fair	Good	Excellent
Pre-test (24)	**58.95**	**16.54**	**16.05**	**7.35**	**1.10**
Ox.–Red. (9)	48.37	21.24	20.26	8.50	1.63
Galvanic (15)	65.29	13.73	13.53	6.67	0.78
Post-test (24)	**9.93**	**10.05**	**13.84**	**15.81**	**50.34**
Ox.–Red. (9)	26.54	7.52	14.38	16.67	54.90
Galvanic (15)	11.96	11.57	13.53	15.29	47.65
Change (24)	**−49.02**	**−6.50**	**−2.20**	**8.46**	**49.26**
Ox.–Red. (9)	−41.83	−13.72	−13.72	8.17	53.27
Galvanic (15)	−53.33	−2.16	0.00	8.62	46.87

Students' alternative conceptions and misconceptions in the explanation tier of the conceptual tests were consistent with the summarized alternative conceptions in electrochemistry by Karsli and Çalik (2012). The alternative conceptions included: (1) the cathode electrode is negatively charged, which allows an oxidation reaction to occur, (2) the anode electrode is positively charged, which allows a reduction to occur, and (3) there was a lack of ability to write the correct cell reactions. The misconceptions were also consistent with the common misconceptions summarized by Sanger and Greenbowe (1997b), such as the anode is positively charged and getting smaller because it lost electrons, while the cathode is negatively charged and getting larger because it gained electrons.

The improvement of students' conceptual understanding and the conceptual changes to the more correct scientific conception categories are consistent with the studies by Cullen and Pentecost (2011) and by Huddle *et al.* (2000) who found that the use of a paper model of a galvanic cell in conjunction with electrochemistry laboratory activities allowed students to visualize what happens at the sub-microscopic level of a galvanic cell. As a result, students gained more conceptual understanding of galvanic cells.

Students' scores in the mental models of a galvanic cell

Prior to the intervention, students' mean scores for the pre-mental models in the macroscopic and symbolic (MacSym) and sub-microscopic (Mol) features were 1.85, 2.35, and 4.21 respectively. After the intervention, their mean scores for the post-models were 3.56, 5.98, and 9.55, respectively (Table 5). The percentages of the actual gains in their mental model scores were 34.20, 36.30, and 35.60 respectively. In addition, the normalized gains for their mental models were 0.54, 0.49, and 0.49, all falling in the medium gain range. The paired-samples T-test analysis indicated that these changes from pre- to post-drawings were statistically significant in all cases. Students obtained a percentage for

Table 5 Students' mental model scores on a galvanic cell (n = 34)

Criteria[b] (score)	Pre-models			Post-models			Gain		
	Mean	SD	%	Mean	SD	%	% Actual	$\langle g \rangle$	T
MacSym A1 (2)	0.82	0.71	41.00	1.41	0.55	70.50	29.50	0.50	3.37[a]
MacSym A2 (2)	0.65	0.63	32.50	1.42	0.49	71.00	38.50	0.57	5.74[a]
MacSym A3 (1)	0.38	0.33	38.00	0.73	0.28	73.00	35.00	0.55	4.54[a]
MacSym total (5)	1.85	1.11	37.00	3.56	1.30	71.20	34.20	0.54	5.66[a]
Mol B1 (4)	1.06	1.04	26.50	2.48	1.31	62.00	35.50	0.49	3.92[a]
Mol B2 (4)	0.85	1.08	21.25	2.30	1.21	57.50	36.25	0.47	3.88[a]
Mol B3 (2)	0.44	0.50	22.00	1.20	0.60	60.00	38.00	0.50	4.23[a]
Mol total (10)	2.35	2.45	23.50	5.98	2.93	59.80	36.30	0.49	4.14[a]
Grand total (15)	4.21	2.88	28.06	9.55	4.10	63.67	35.60	0.49	4.81[a]

[a] Statistically different at the significance level of 0.05. [b] Criteria MacSym A1–A3 and Mol B1–B3 are described in the data analysis.

Table 6 Percentages of students in 5 conceptual categories in mental model drawings (n = 34)

Mental models	Percentage of students (%) NU	MU	PMU	PU	SU
Total pre-test	**38.24**	**24.51**	**21.08**	**10.29**	**5.88**
MacSym criteria	**29.41**	**26.47**	**21.57**	**10.78**	**11.76**
MacSym A1	23.53	32.35	17.65	8.82	17.65
MacSym A2	32.35	32.35	17.65	8.82	8.82
MacSym A3	32.35	14.70	29.41	14.70	8.82
Mol criteria	**47.06**	**22.55**	**20.59**	**9.80**	**0.00**
Mol B1	41.18	20.59	29.41	8.82	0.00
Mol B2	52.94	20.59	14.70	11.76	0.00
Mol B3	47.06	26.47	17.65	8.82	0.00
Total post-test	**5.88**	**13.72**	**23.04**	**32.84**	**24.51**
MacSym criteria	**0.00**	**15.69**	**20.59**	**31.37**	**32.35**
MacSym A1	0.00	17.65	20.59	29.41	32.35
MacSym A2	0.00	11.76	23.53	38.24	26.47
MacSym A3	0.00	17.65	17.65	26.47	38.24
Mol criteria	**11.76**	**11.76**	**25.49**	**34.31**	**16.67**
Mol B1	11.76	11.76	23.53	29.41	23.53
Mol B2	11.76	14.70	23.53	38.24	11.76
Mol B3	11.76	8.82	29.41	35.29	14.70
Total change	**−32.35**	**−10.78**	**1.96**	**22.55**	**18.63**
MacSym criteria	**−29.41**	**−10.78**	**−0.98**	**20.59**	**20.59**
MacSym A1	−23.53	−14.70	2.94	20.59	14.70
MacSym A2	−32.35	−20.59	5.88	29.41	17.65
MacSym A3	−32.35	2.94	−11.76	11.76	29.41
Mol criteria	**−35.29**	**−10.78**	**4.90**	**24.51**	**16.67**
Mol B1	−29.41	−8.82	−5.88	20.59	23.53
Mol B2	−41.18	−5.88	8.82	26.47	11.76
Mol B3	−35.29	−17.65	11.76	26.47	14.70

the pre-mental model score of 37.00 for macroscopic features, much higher than the 23.50 for sub-microscopic features. An explanation of this may be that students find sub-microscopic features difficult to understand due to their intangibility and/or invisibility (Coll and Treagust, 2003; Chandrasegaran *et al.*, 2011). However, after involvement in the corresponding experiments and models, the percentage in the mean post-mental model score regarding sub-microscopic features increased to 59.80. This improvement of 36.30 indicated that the small-scale experiments of electrochemistry in conjunction with the model kit of galvanic cells were effective in the enhancement of the students' mental models.

Students' conceptual categories in mental models of a galvanic cell

The students were categorized into five groups regarding their information expressed in their mental model drawings. When asked to draw mental models of how they understand what happens at the molecular (or sub-microscopic) level in galvanic cells, the categorization of the students' macroscopic and symbolic (MacSym) information at the pre-stage fell mostly in NU (29.41%), MU (26.47%), and PMU (21.57%), and their molecular information for the same stage was also categorized mostly in NU (47.06%), MU (22.55%), and PMU (20.59%), see Table 6. This indicated that prior to the intervention most students accommodate specific misconceptions at both macroscopic (including symbolic) and sub-microscopic levels in all scientific concepts of galvanic cells (see also Table 2). In addition, there were no students in the SU group at the sub-microscopic level in this stage.

After the intervention, their models moved to more correct conceptual understanding categories. For macroscopic and symbolic information, most students were in SU (32.35%) and PU (31.37%) and no students in NU. MacSym A3 (oxidation and reduction half-cells) and MacSym A1 (electrodes, solutions and salt bridges) were the criteria that most students obtained sound understanding (38.24%, 32.35%) over partial understanding (26.47%, 29.41%), while MacSym A2 (particles) was the criterion that most students obtained partial understanding (38.24%) over sound understanding (26.47%). However, there were some students who fell in the MU. The scientific concepts that many students tended to accommodate misconceptions at macroscopic and symbolic levels included (1) switching anode and cathode (Mac), (2) proving incorrect oxidation number for metal ions (*Sym*), (3) switching oxidation and reduction half-cells (Mac), and (4) providing total oxidation–reaction equation without awareness of mole of electrons (*Sym*).

For sub-microscopic information, most were categorized in PU (34.31%) and PMU (25.49%), while some of them were in SU (16.67%). Most students obtained partial understanding over partial understanding with specific misconception in all criteria of molecular feature. Mol B1 (position of particles) was the criterion that students tended to have sound understanding over Mol B2 (numbers of particles) and Mol B3 (transfer of particles). However, there were some students who fell in the MU and NU. The scientific concepts that many students tended to accommodate misconceptions at the molecular level included (1) numbers of neutral atoms increases in the anode, while decreases in the cathode, (2) numbers of metal cations increases in the reduction half-cell, while decreases in the oxidation half-cell, (3) proving wrong oxidation number or oxidation state of metal ions in each half-cell, (4) no transfer of salt-generated ions from one to the other half-cell, and (5) no electrolytic anions transfer from one to the other half-cell.

For the conceptual changes, the majority of students moved from the less understanding (NU + MU) to the more understanding (PU + SU) categories in the macroscopic features. The order of NU + MU decreases was MacSym A2 (52.94%), MacSym A1 (38.23%), and MacSym A3 (29.41%), respectively. On the other hand, the order of PU + SU increases was MacSym A2 (47.06%), MacSym A3 (41.17%), and MacSym A1 (35.29%), respectively. In other words, the conceptual changes from the less understanding (NU + MU) to the more understanding (PU + SU) categories of MacSym A2, A1, and A3 were 100%, 73.52% and 70.58%. This finding indicated that this intervention promoted students' conceptual changes at the macroscopic level in scientific concepts of MacSym A2 over concepts of MacSym A1 and MacSym A3. For the sub-microscopic features, the order of NU + MU decreases was Mol B3 (52.94%), Mol B2 (47.06%), and Mol B1 (38.23%), respectively. On the other hand, the order of PU + SU increases was Mol B1 (44.12%), Mol B3 (41.17%), and Mol B2 (38.23%), respectively. In other words, the conceptual changes from the less understanding (NU + MU) to the more understanding (PU + SU) categories of Mol B3, B2, and B1 were 94.11%, 85.29% and 82.35%. This finding indicated that this intervention promoted students' conceptual changes at the sub-microscopic level in scientific concepts of Mol B3 over concepts of Mol B2 and Mol B1.

The improvement of students' mental models of galvanic cells and the changes of their mental model categories to the more correct categories may arise from the fact that the model of galvanic cells provided students a chance to access the sub-microscopic level to direct perception. The students can construct or transform their own mental models based on the sub-microscopic information obtained from the model and macroscopic information from the experiments (Glynn and Duit, 1995; Briggs and Bodner, 2005; Doymus *et al.*, 2010; Dixon and Johnson, 2011). This supported students to relate macroscopic and symbolic information to sub-microscopic information. They then generated reasonable mental (or conceptual) models and used these models to achieve full understanding of these intangible electrochemistry concepts (Johnstone, 1993; Doymus *et al.*, 2010; Dixon and Johnson, 2011; Duis, 2011).

Examples of students' mental models of galvanic cells

Consider the mental model drawings of a Ni–Cu galvanic cell of Student A. Prior to the involvement of the experiment, Student A provided partial understanding (PU) information that Ni^{2+} and Cu^{2+} ions appear in solution, as shown in Fig. 6a.

However, she provided incomplete information, no Ni and Cu atoms present. After involvement of the corresponding experiment, she noticed her incomplete information and changed her post-mental model to the more correct understanding (Fig. 6b). However, she provided new mis-understanding (MU) information

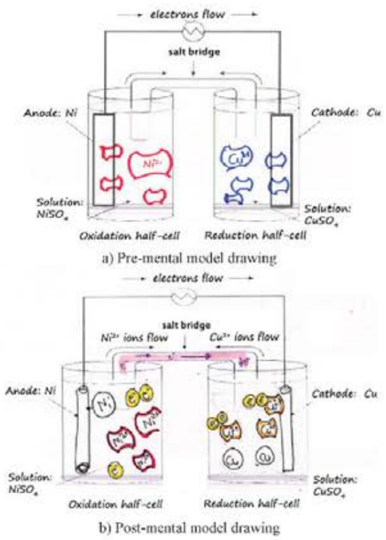

Fig. 6 Sub-microscopic mental models for a Ni–Cu galvanic cell of Student A.

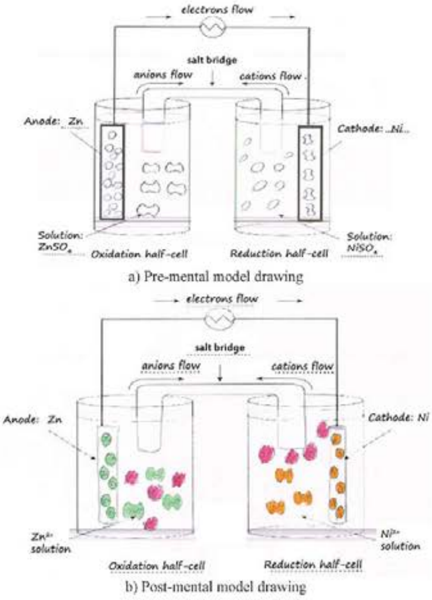

Fig. 7 Sub-microscopic mental models for a Zn–Ni galvanic cell of Student B.

that Ni^{2+} and Cu^{2+} ions transferred from one to the other half-cell and electrons transferred *via* the salt bridge. She also provided mis-understanding (MU) information that when Cu^{2+} ions received 2 electrons they became the Cu atoms and appeared in the solution instead of the cathode electrode. She provided partial understanding (PU) information that when Ni atoms gave two electrons they became Ni^{2+} ions and appeared in solution.

Consider the mental model drawings of a Zn–Ni galvanic cell of Student B. Prior to the involvement of the electrochemistry experiment, Student B provided sound understanding (SU) information in the oxidation half-cell that Zn atoms appear in the Zn anode, while Zn^{2+} ions appear in the solution, as shown in Fig. 7a. However, she provided partial understanding and mis-understanding (PMU) information in the reduction half-cell that Zn^{2+} ions appear in the Zn anode, while Zn atoms appear in the solution. After involvement of the electrochemistry experiment, she noticed her mis-understanding and changed her post-mental model to the more correct understanding (Fig. 7b).

Most students provided more complete macroscopic information than molecular information at both the pre- and post-stages as the former is not difficult to understand due to images shown in learning materials and more obvious observations of changes in the experiments. The reason for the students' higher post-stage score may be due to the fact that after the experience of the experiments, the students obtained relevant information by observation of the experiments, leading to modification of their mental models to provide more reasonable explanations of what happens at the molecular level of the given galvanic cells. However, some students' modified models may still contain mis-conceptions (Piquette and Heikkinen, 2005).

Students' alternative- and mis-conceptions encountered in their mental model drawings of a galvanic cell at a sub-microscopic level in this study were mostly consistent with the summaries by Karsli and Çalik (2012) and by Sanger and Greenbowe (1997b). For example, they understood that the cathode is an oxidation half-cell that loses electrons, and decreases mass over time, while the anode is a reduction half-cell that gains electrons, and increases mass over time (Karsli and Çalik, 2012). Some of them thought that the salt bridge allows electrons to travel from the anode to the cathode without assistance from the ions (Sanger and Greenbowe, 1997b) and allows the electrolytic cations migrate toward the anode electrode, whereas the electrolytic anions migrate towards the cathode electrode (Karsli and Çalik, 2012). Some students understood that electrons move through solution from one to the other by attaching themselves to ions (Sanger and Greenbowe, 1997b), while cations in the electrolyte solution transfer from the cathode to the anode by accepting electrons (Sanger and Greenbowe, 1997b), and so on.

In addition, the analysis of mental models of galvanic cells together with the informal unstructured interview regarding their models revealed some potential causes that can lead to misconceptions at the sub-microscopic level of galvanic cells. These causes were shown below.

(1) Number of neutral atoms. Many students misunderstood that the number of neutral atoms increases in the anode, while it decreases in the cathode. This arose from the confusion between the changes of anode and cathode electrodes. Many of them thought that the number remains constant because the experiments that they conducted may not be long enough to obviously notice the change of any metal electrodes although the model kit illustrated this change.

(2) Number of metal cations. Many students misunderstood that the number of metal cations increases in the reduction half-cell, while it decreases in the oxidation half-cell. This arose from the confusion between the changes of oxidation and reduction half-cells. Some of them thought that the number remains constant in both half-cells, or changes (increases or decreases) only in the oxidation or reduction half-cell. This could arise from the fact that some galvanic cells obviously changed colour only in one half-cell (*i.e.*, the colour change can be observed only in the Cu reduction half-cell of the Zn–Cu cell). Therefore, they thought that the number of ions must be constant in the unchanged solution. The number of metal cations and electrons as well as neutral atoms model activity should be more emphasized to minimize the first and second issues.

(3) Oxidation number. Many students identified an incorrect oxidation number for metal cations in each half-cell. This occurred because they could not provide the correct dissolution equation of salt in water, which led to the incorrect oxidation states. Some of them just misremember the oxidation states or for each metal ion and electrolytic anion. The latter case was considered as a mistake rather than a misconception.

(4) Transfer of salt-generated ions. Many students misunderstood that salt-generated cations transferred from the reduction to oxidation half-cell, while anions transferred from the oxidation to reduction half-cell. Some of them thought that no ions transfer but electrons. This arose because the model activity sometimes allowed students to omit salt-generated ions. Therefore, they may not able to notice this change.

(5) Transfer of electrolytic anions. Many of them did not notice the transfer of electrolytic anions from the reduction to oxidation half-cell to balance the new generated metal cations. This arose because they thought that salt-generated ions already transferred from one to the other half-cell. Therefore, electrolytic anions should remain in their half-cell.

These misconceptions were consistent with the previous studies (Sanger and Greenbowe, 1997b; Karsli and Çalik, 2012). However, these encounter misconceptions will be further studied in attempt to minimize them and change them to the more correct conceptions.

The model kit demonstration together with class discussion could diminish the misconceptions about the numbers of neutral atoms and metal cations and the transfer of salt-generated ions and electrolytic anions. In addition, class discussion about the dissolution equations of common salts in water can decrease misconceptions about oxidation states or oxidation numbers. Once students can provide correct states for both cations and anions, they are expected to provide correct oxidation numbers for each metal ion.

In short, the corresponding small-scale experiments allowed students to observe what occurs at a macroscopic level and relate the macroscopic observation to a symbolic level (chemical formulas and equations). This Green chemistry based experiment can diminish the amounts of chemicals used, toxic chemicals, and generated-wastes, while preserve concepts of the experiments, and necessary laboratory techniques and skills (Poliakoff and Licence, 2007; Martin and Gilbert, 2011). Moreover, the corresponding model of galvanic cells, which was inexpensive, portable and flexible, can diminish the difficulty in sub-microscopic visualization and allow students to link the macroscopic experiment observation and symbolic levels to the sub-microscopic level. Once students were able to visualize and relate among the macroscopic, symbolic and sub-microscopic representations, their conceptual understandings of electrochemistry concepts were effectively improved (Chittleborough and Treagust, 2007; Çalik *et al.*, 2010). In addition, the 5E inquiry learning approach also actively engaged students to scientific questions and to explore the answers for these questions through an inquiry process (Deters, 2005). This study also verified that discussion in a small group and in a class with the instructor facilitation effectively enhanced students' conceptual understanding as they gained their understanding and corrected their alternative conceptions while discussing with their peers (Cullen and Pentecost, 2011).

Conclusion and implications

The study results verified that the intervention of the low-cost and small-scale experiments of electrochemistry in conjunction with the inexpensive, portable, reproducible, and flexible model kit by using the 5E inquiry learning approach was effective to enhance students' conceptual understanding and mental models of corresponding concepts. The students obtained a mean post-conceptual test score statistically higher than the pre-conceptual test score. The majorities of the pre-conceptual test were from the choice part but after the intervention, the explanation part played a more important role in their post- than in their pre-conceptual test scores. Before the intervention, most students were in the partial understanding with specific misunderstanding (PMU) to no understanding (NU) categories, but after the intervention they moved to the more correct scientific conceptions, partial understanding (PU) to partial understanding with specific misunderstanding (PMU) categories. For the mental models, the students obtained a mean post-mental model score statistically higher than the pre-mental model score. The majorities of the pre-experiment scores were from the macroscopic part in their mental models, but the sub-microscopic part played more important role in their post-experiment scores than in the pre-experimental scores. Prior to the intervention, the majority of students were in the partial understanding with specific misunderstanding (PMU) to no understanding (NU) categories, but they moved to the better scientific conceptions, partial understanding (PU) to partial understanding with specific misunderstanding (PMU) categories, after the intervention. The major misconceptions encountered in students' mental models of galvanic cells included (1) the number of neutral atoms increases in the anode, while it decreases in the cathode, (2) the number of metal cations increases in the reduction half-cell, while it decreases in the oxidation half-cell, (3) identified incorrect oxidation state for metal cations in each half-cell, (4) salt-generated cations transferred from the reduction to oxidation half-cell, while anions transferred from the oxidation to reduction half-cell, and (5) unaware of transfer of electrolytic anions from the reduction to oxidation half-cell.

This study may have implications for chemistry instructors in that teaching or directing students to perform an experiment might be not enough to help students understand important concepts at the molecular level. Chemistry instructors should consider using a corresponding model featuring the sub-microscopic level or various tools such as jigsaws, simulations, animations, virtual laboratory (Hawkins and Phelps, 2013) or other visualization tools (Osman and Tien Lee, 2014) to help students visualize concepts at the molecular level and then connect these concepts to the corresponding macroscopic experiment observations (Doymus *et al.*, 2010). The use of a cooperative learning approach should be considered to let students learn and understand the concepts from their peers (Acar and Tarhan, 2007). As a result, students may achieve a complete and lasting conceptual understanding (Doymus *et al.*, 2010). It is advisable that numbers of neutral atoms, metal cations, and electrons should be emphasized in regard to mole concepts.

There were some limitations in this study. One of these was about the use of a two-tier multiple choice test with the open explanation/reason in the second tier. The author found it difficult to encourage students to supply their reasons for their responses in the first tier. The use of a two-tier test with multiple choices or other forms of test may be considered to diminish this limitation. In addition, using students' explanations to construct 2-tier multiple-choice items is advisable to avoid this limitation. Another limitation was that the same pre- and post tests were used in this study. This was considered as a weak methodology because improvements could be observed with almost any other learning approach. The parallel test or equivalence test should be used to avoid this limitation. The last limitation was about one group pre-test/post-test design without control group. This could be questionable about the effectiveness of this intervention. The design with control and treatment group is advised to diminish this limitation.

For the further study, the information about students' conceptual understanding of electrochemistry and about mental models of a galvanic cell will be used in the design and development of a molecular animation to support students' acquisition to understand electrochemistry concepts or to generate the more correct mental models (Markman, 1999). The content taught to students will be designed to be more contextualized in real situations to promote students to connect between the content and everyday life contexts. The small-scale experiments incorporated with corresponding molecular animation will be implemented to investigate how they impact students' conceptual understandings and mental models of electrochemistry.

Acknowledgements

This study was part of the TRG5680024 project entitled "Development of Inquiry Chemistry Experiments in conjunction with Molecular Animations (ICEMA) to Promote High School Students' Conceptual Understanding and Conceptual Change at the Molecular Level", co-funded by Thailand Research Fund (TRF) and Ubon Ratchathani University (UBU). The author thanks Richard E. Coll at University of Fiji for a detailed review of the manuscript. The author also thanks Bob Tremayne of the Office of International Relations at Ubon Ratchathani University (UBU) for assistance with English editing and thanks Nutjaree Supasorn (class instructor) and her grade 12 students during academic year 2014 at Srimuang Wittayakhan School for their fruitful participation.

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Chemistry Education Research and Practice

PAPER

View Article Online
View Journal | View Issue

Cite this: *Chem. Educ. Res. Pract.*, 2015, **16**, 121

Implementation of 5E inquiry incorporated with analogy learning approach to enhance conceptual understanding of chemical reaction rate for grade 11 students

Saksri Supasorn*[a] and Vinich Promarak[b]

Received 12th September 2014, Accepted 29th October 2014

DOI: 10.1039/c4rp00190g

www.rsc.org/cerp

The main purpose of this study was to enhance student understanding of the scientific concepts of chemical reaction rate. Forty-four grade 11 students were the target group. The treatment tools were seven learning plans of 5E inquiry incorporated with an analogy learning approach during 15 hours of class time. In each learning plan, the students (1) addressed a scientific question regarding chemical reaction rate, (2) explored evidence to answer the question by carrying out a corresponding experiment, (3) drew explanations from collected evidence to answer the question, (4) elaborated their understanding by studying the given analogy and the target, and (5) evaluated their conceptual understandings by creating their own analogy and identifying similarities and differences of their analogies and the targets. The data collecting tool was a conceptual test of chemical reaction rate, consisting of 30 two-tier three-choice questions. The normalized learning gain for the whole conceptual test was at the medium gain level (0.64). The dependent samples *t*-test analysis indicated that the post-conceptual test score (mean 45.32, SD 6.46) was statistically higher than the pre-test score (mean 19.70, SD 3.10), but was statistically lower than the retention test score (mean 48.03, SD 9.04) at the significance level of 0.05. In the pre-conceptual test, the percentages of students in the good-, alternative-, and misconception categories were 13.69, 38.45, and 47.86, respectively. In the post-conceptual test, the percentages of students in these categories were 64.72, 24.6, and 10.63, respectively. This finding indicates that this implementation was an effective means to enhance and retain students' conceptual understanding of chemical reaction rate.

Introduction and background

Chemical reaction rate, or chemical kinetics, has been found to be one of the most difficult chemistry topics to understand because it involves mathematical calculations and because there are many factors influencing the reaction rate (Justi, 2003). Thai students exhibit the same learning difficulties as those reported for other students (Chairam *et al.*, 2009). Some students have an alternative understanding of concepts which are not consistent with the consensus of the scientific community (Mulford and Robinson, 2002; Taber, 2002). Their understanding of concepts may be partially right, but incomplete or just simply wrong (Piquette and Heikkinen, 2005). Requiring students to generate their own analogues (also called analogical models) and to identify how their analogues are similar to and/or different from the targets (also called target concepts) of the corresponding concepts can reveal their conceptual understandings and identify some of their alternative conceptions. This information is useful for devising corresponding analogues that best support students' concept acquisition.

[a] *Ubon Ratchathani University, Faculty of Science, Ubon Ratchathani, 34190, Thailand. E-mail: saksri.supasorn@gmail.com*
[b] *Suranaree University of Technology, Institute of Science, Nakhon Ratchasima, 30000, Thailand*

Chemical reaction rate

The term "reaction rate" is not a property of chemical species themselves it is a property of the extent of a reaction (Schmitz, 2005). Cunningham (2007) commented that descriptions of methods for helping students to understand reaction rate have been presented in many textbooks, but there has been little discussion of how to gain students' understanding by asking them to find their own meaning of reaction rate. He designed the following assignments to help students enhance their understanding of reaction rate and to assess that understanding:

(1) Can the student identify a change that is clearly chemical, as opposed to physical, in nature?

(2) Can the student identify a chemical reaction whose increased or decreased rate is of some interest or practical importance?

(3) Can the student correctly identify the reactants and products of the chemical change they have selected?

(4) Can the student clearly and correctly explain the mechanism by which the factor identified increase, and

(5) Can the student effectively apply the standard conventions of written English?

Many studies have been carried out on students' conception of the topic of chemical reaction rate or chemical kinetics. For example, Van Driel (2002) attempted to develop grade 10 students' ideas of macroscopic chemical phenomena together with their views of the particulate nature of matter. The students were requested to carry out chemical experiments and explain their experimental results. He concluded that students of this age in the Netherlands have limited abilities for reasoning in corpuscular terms. His approach has the potential to aid students to move from primitive corpuscular to more scientifically acceptable views. Although, student explanations may be deficient from a scientific perspective, students gradually learn to become more proficient in using corpuscular models as explanatory tools.

Another example is the investigation carried out by Chairam *et al.* (2009) on the study of chemical kinetics by Thai students. They reported that chemical kinetics is an extremely important concept taught in introductory chemistry courses. The teaching of chemical kinetics to high school and undergraduate students in Thailand generally begins with an emphasis on qualitative aspects. Students are often introduced to the rate of reaction and factors (such as temperature, concentration, and catalysts) which influence the rate of a reaction. They also investigated the effect of inquiry-based learning activities in which the first year undergraduate science students at a public university in Thailand were requested to design and carry out an experiment to investigate the reaction of acids and bases. They found that the students were able to develop a good conceptual understanding of chemical kinetics from participation in this more active and enjoyable teaching approach.

The conceptual changes of Turkish grade-11 students was studied by Çalik *et al.* (2010). They examined some previous studies and identified some problems encountered in learning the concept of chemical reaction rate. Some of these problems are (1) an inability to define the rate of reaction, (2) misunderstanding, misapplying or misinterpreting of the relationship between the rate of reaction and its influencing factors, and (3) a lack of understanding of how activation energy and enthalpy relate to the rate of reaction. They also investigated the effects of conceptual change pedagogy on students' conceptions. They found that conceptual change pedagogy intervention helped students to notice and correct their alternative conceptions. They suggested that a combination of various conceptual change methods may be more effective for decreasing students' alternative conceptions. Çalık and his colleague (Kolomuç and Çalık, 2012) also explored the alternative conceptions generated by Turkish chemistry teachers and students (grade 11) for the topic of chemical reaction rate. They found that chemistry teachers and students tended to have similar alternative conceptions, which may be have been transmitted from the chemistry teachers. Examples of some alternative conceptions include: (1) a lack of understanding of the effect of enthalpy on the rate of reaction and mechanism of reaction, and (2) misunderstanding/misapplying of the relationship between temperature or concentration and the rate of reaction.

Actually there are more studies about student conceptions on the concept of 'chemical reaction rate' or 'chemical kinetics' (Bektaşlı and Cakmakcı, 2011; Cakmakci *et al.*, 2006; Çalık *et al.*, 2009b; Cakmakci, 2010), however, details of these studies are not presented in this article.

5E inquiry learning activities in chemistry

There are a number of models of inquiry in learning science. The 5E learning cycle has been proven to be one of the most effective inquiry learning model for chemistry and other sciences and can be applied at several levels in the instructional sequences within lessons (Bybee *et al.*, 2006). The 5E learning cycle involves the following steps:

(1) Engagement – students are engaged in inquiry questions,

(2) Exploration – students plan, design, and carry out their experiment, and record the experiment data,

(3) Explanation – students give explanations from the experimental data to answer the questions,

(4) Elaboration – students extend and apply their findings in a new context, especially a daily life one, and

(5) Evaluation – students evaluate their experimental process and results in a variety of ways, such as an activity report, instructor observation during the activity, and student presentations.

Although other learning cycle models (3E and 7E) have been introduced for chemistry instruction, these models are adapted directly from the 5E instructional model. The 5E learning cycle has many advantages, for example, it promotes active learning process, supports the processing of new information by students based on the extent of their personal knowledge, and improves students' attitudes to chemistry instruction. Inquiry not only supports students' understanding of science concepts but also illustrates how they can construct knowledge themselves through the inquiry learning cycle. In addition, the 5E learning cycle can help students edit their alternative conceptions rather than rely only on textbook-oriented instruction. However, students' alternative conceptions and existing knowledge prior to the inquiry instruction should be explored. This information can be used in designing inquiry activities that support student efforts to correct their alternative conceptions (Balci *et al.*, 2006; Bybee *et al.*, 2006).

Inquiry learning activities have been found to be effective in teaching chemistry and have been widely advocated in the last few decades (Sanger, 2009). These types of activities possess advantages over traditional activities. Students are challenged to practice using learning resources and working in groups to enhance their higher-order cognitive skills (HOCS) or the skills of interpretation, analysis, prediction, and synthesis (Zoller and Tsaparlis, 1997; Bybee *et al.*, 2006; Zoller and Levy Nahum, 2012). The instructors tend to play a role as facilitators who motivate and challenge students to carry out the activities through a science inquiry process (Deters, 2005). Moreover, instructors who continuously implement a 5E learning cycle tend to ask higher-order cognitive skill (HOCS) questions more often than non-5E instructors, who ask recognition and recall questions (Bybee *et al.*, 2006).

Based on the findings of the studies detailed above, the topic of chemical reaction rate or chemical kinetics can be said to play an important role in learning subsequent related chemistry topics but students in many countries (both secondary and undergraduate students) tend to have alternative conceptions (Kolomuç and Çalık, 2012). Inquiry-based experiments or activities are proven to be effective means to help students overcome their alternative conceptions and change to more correct conceptions (Chairam *et al.*, 2009; Van Driel, 2002).

Analogies in chemistry learning

Based on the assumption of Sarantopoulos and Tsaparlis (2004), an analogy is a system of relations (correspondences) between parts of the structure of two domains: the analogue and the target. The analogue domain, also called the source or base domain, is a domain that exists in memory, from which the analogy is drawn. The target domain contains the scientific concept, the learning objective of the analogy. An analogy involves the transfer of relational information from the analogue to the target, which consists of finding the correspondences between the two systems.

Previous research studies suggested some instructional models for teaching with analogies. The FAR (Focus, Action, and Reflection) guide is one of the most common models used in analogy learning in science (Harrison and Treagust, 2006; Harrison and Coll, 2007). This model was proposed to maximize the benefits and minimize the problems encountered in analogy instruction (Venville, 2008). In the *Focus* phase, the scientific (target) concept and student familiarity with the analogue are considered. This can guide pre-lesson planning by focusing attention on issues of concept complexity, prior student knowledge, and experience with the analogy. In the *Action* phase, students experience the analogical model and identify the similarities and dissimilarities (or differences) of the analogue and the target concept. Various methods can be used to help the students identify similarities and differences between the analogue and target concept. The *Reflection* phase takes place after the presentation of the analogy in this phase the instructor reflects upon the clarity and usefulness, and conclusions drawn from the analogue. This phase prompts the teacher to consider the clarity and usefulness of the analogy and to re-focus on the previous phases as necessary (Venville, 2008; Davis, 2013). The three typical phases in the FAR guide model for teaching with analogies are illustrated in Table 1 (Venville, 2008; Davis, 2013).

Table 1 The three phases in the FAR guide model (Venville, 2008; Davis, 2013)

Focus phase	Pre-lesson planning
Concept	Is the concept difficult or abstract? What is difficult about the concept?
Students	What ideas do students currently have about the concept?
Experience	What familiar experiences do students have that I can use?
Action phase	**In-lesson action**
Similarities	Cue the student memory of the analogy Discuss ways in which the analogue is like the target Are there surface features or deep relations?
Differences	Discuss ways in which the analogue is unlike the target
Summary	Conclude by summarising the outcomes of using the analogy
Reflection phase	**Post-lesson reflection**
Conclusions	Was the analogy clear and useful, or confusing?
Improvements	What changes are needed for the following lesson? What changes are needed the next time I use this analogy?

In previous decades many outstanding studies have been carried out on analogy learning in chemistry. For example, Çalık and Ayas (2005) devised an analogy learning activity based on students' alternative conceptions about solution chemistry from their previous study to address students' alternative conceptions of solution chemistry. They found that this alternative teaching method was generally successful, however, its applicability has not been investigated. They finally suggested that analogies can effectively make intangible concepts tangible for students when the used analogies support students to clearly connect between the analogue and target concepts. Çalik further investigated the effectiveness of an analogy activity in improving students' conceptual change of solution chemistry concepts with his colleagues (Çalik *et al.*, 2009a). They used 'travel on a public bus' as the analogy activity. They found that most of the students' pre-test responses were in the No Understanding (NU) category. Some of the students' alternative conceptions were about using incorrect scientific terms (*i.e.*, use of the words 'less saturated' or 'diluted' instead of 'unsaturated', and 'concentrated' instead of 'saturated') and difficulty in differentiating the terms (*i.e.*, the terms 'melting' and 'dissolving'). However, the majority of their post-test and delayed post-test responses moved to the more understanding categories, Partial Understanding with Specific Alternative Conception (PU + AU), Partial Understanding (PU), and Sound Understanding (SU). They then suggested that in such analogy learning activities if student self-assessment is to be used, the intervention time should be planned carefully.

Orgill and Bodner (2004) reported that analogies can be powerful teaching tools because they can make new material intelligible to students. Many students enjoy, pay particular attention to, and remember the analogies that their instructors provide. Although some analogies are not as effective as others, these analogies do help students to understand, visualize, and recall what they have learned in class. This is consistent with the findings of Harrison and Coll (2007), who reported that analogies are often used in science to engage student interest and to explain difficult and abstract ideas. While some analogies effectively clarify difficult concepts, many are inadequate or can cause further confusion. Eskandar *et al.* (2013) also suggested that teaching chemistry with textual elaborated analogies can also enhance students' logical thinking ability. However, they reported that although all the students stated that they were familiar with analogy concepts in science textbooks, it is likely that some were less familiar than others.

Çalik *et al.* (2009a) reviewed previous studies on teaching chemistry with analogies and concluded that teaching using multiple analogies is better than teaching using a single analogy.

They also suggested some key features for effective analogy instruction: (1) ensuring the analogy is familiar to the students, (2) mapping as many shared attributes as possible, and (3) identifying where the analogy breaks down.

The previous studies suggested that learning chemistry by using familiar analogies is usually effective at promoting student conceptual changes (Çalik *et al.*, 2010). Analogies allow students to understand even intangible chemistry concepts since they aid students to relate between the analogue and target concepts (Çalık and Ayas, 2005).

Inquiry learning activities are effective demonstrations of tangible chemistry (*i.e.*, macroscopic) concepts, and the analogies make it possible for students to understand intangible chemistry (*i.e.*, molecular or sub-microscopic) concepts. Therefore, the combination of inquiry and analogy learning approaches could enhance students' understanding of both tangible and intangible chemistry concepts.

Research questions

The main purpose of this study was to develop inquiry activities that incorporate analogies and to use these activities as a means of enhancing and retaining students' conceptual understanding of chemical reaction rate. When the activities were implemented, the following questions were posed:

1. How does the implementation of inquiry activities that incorporate analogies enhance and retain students' conceptual understanding of chemical reaction rate?

2. How do the percentages of students having good conceptions, alternative conceptions, or misconceptions of chemical reaction rate change after they complete inquiry activities that incorporate analogies?

Research methodology

The details of the methodology for this study are as follows.

Treatment tools

The treatment tools consisted of seven learning plans (totalling 15 hours) of inquiry combined with analogy learning activities for instruction, as shown in Table 2, while an example of the FAR guide model for the topic of "effect of a catalyst or a retarder on chemical reaction rate" is illustrated in Table 3.

Table 2 Key activities of the inquiry incorporated with analogy learning activities

Learning plans (hours)	Key activities (E = experiment, A = analogy)
1. Definition and calculation of reaction rate (3)	– A: running various distances within a limited time.
2. Theories of reaction rate (2)	– A: blowing a clay ball up various slopes.
3. Effect of nature of substances on reaction rate (2)	– E: reactions of various shells (egg, crab, or mollusc) with various acids. – A: sailing paper boats of various-thickness.
4. Effect of surface area on reaction rate (2)	– E: reactions of acid and various-sized shells. – A: dissolving table and crystalline sugars in water.
5. Effect of concentration on reaction rate (2)	– E: reactions of various-concentrations of acids and a specific shell (egg, crab, or mollusc). – Analogy: increasing number of identical images in the image matching game.
6. Effect of catalyst and retarder on reaction rate (2)	– E: effects of manganese sulfate ($MnSO_4$) and sodium fluoride (NaF) on the reaction of oxalic acid ($H_2C_2O_4$) and sulfuric acid (H_2SO_4). – A: blowing a clay ball up various slopes.
7. Effect of temperature on reaction rate (2)	– E: reactions of acid and a specific shell at various temperatures. – A: cooking popcorn at various temperatures.

Table 3 Example of the FAR guide model for the effect of a catalyst and a retarder

Focus phase	Pre-less on planning
Concept	– How a catalyst and retarder affect the chemical reaction rate is difficult to understand.
Students	– Already understand that a catalyzed reaction occurs faster or a non-catalyzed reaction occurs slower than a normal reaction, but do not understand the mechanism of how a catalyst or a retarder affect the rate.
Experience	– Riding a bicycle, riding a motorcycle, driving a car uphill, and walking up stairs.
Action phase	**In-lesson action**
Similarities	– Slope of hill and amount of activation energy (E_a). – Time for riding and reaction time. – Power used for riding and reaction energy.
Differences	– Slope of hill may remain the same but the amount of activation energy (E_a) can be decreased or increased. – Riding, driving, or walking to the top is a physical change (no product), but a reaction is a chemical change (product generated). – People who are biking and walking uphill may feel tired, but reactants do not have feelings.
Reflection phase	**Post-lesson reflection**
Conclusions	– Riding a motorcycle and driving a car uphill do not involve feeling tired (clear analogies).
Improvements	– Riding a bicycle uphill and walking up stairs are tiring and this should not be taken into account in these analogies. – More explanation about decreasing or increasing of E_a caused by a catalyst or a retarder.

In each learning plan, the intervention process of the 5E inquiry cycle incorporated an analogy with FAR guide learning as shown below:

(1) Students were presented with a scientific question regarding chemical reaction rates.

(2) Students explored evidence (or data) to answer the question by planning and carrying out a corresponding experiment.

(3) Students came up with an explanation from collected evidence (or data) to answer the question.

(4) Students elaborated their understanding through a corresponding analogy by identifying similarities and differences between the given analogue and the target, following FAR guide analogy instruction (Harrison and Coll, 2007).

(5) Students were asked to generate their own analogy and then identify the similarities and differences between their analogues with the targets to evaluate their conceptual understanding.

Data collecting tool

The data collecting tool was a conceptual test on chemical reaction rates and consisted of 30 two-tier three-choice questions. The two-tier multiple choice questions were developed specifically for the purpose of identifying students' alternative conceptions about various concepts in limited and clearly defined content areas (Chandrasegaran *et al.*, 2007). The items were content-validated by two senior lecturers of chemistry and one professor of chemical education. Each question comprised two tiers and the students were required to make their choice of answer for the content question in the first tier, and then select the explanation or reason for that choice in the second tier (22 items out of 30 items or 73.33%). Examples of the conceptual test questions are shown in Fig. 1. For some questions, students were asked to supply calculation methods for the response that they had selected instead of selecting the explanation choice (8 items out of 30 items or 26.67%), see also Fig. 2 (Treagust, 1988).

The difficulty index (*P*), discrimination index (*r*), and reliability were calculated by using the *Simple Item Analysis* or *SIA* software, which is generally used in many schools in Thailand. The difficulty index (*P*) for each item was in the range of 0.20–0.80, in which the percentages of items with *P* in the ranges of 0.20–0.39, 0.40–0.59, and 0.60–0.80 were 20.00, 70.00, and 10.00, respectively. The discrimination index (*r*) for each item was in the range of 0.27–1.00, in which the percentages of items with *r* in the ranges of 0.20–0.39, 0.40–0.59, 0.60–0.79, and 0.80–1.00 were 6.67, 36.67, 46.67, and 10.00, respectively. In addition, the reliability based on the Kuder–Richardson formula 20 or KR_{20} for the entire test was 0.85.

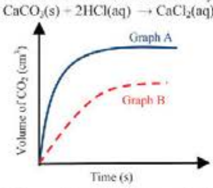
Note that all of the research tools including the treatment tools (lesson plans) and data collecting tools (conceptual tests, analogies, and interview) were in Thai. The class was taught in Thai and all the examples included in this article involved translation into English.

Participants

With prior permission from the school principal and the instructor of the chemistry course taught during the second semester of academic year 2013, 44 students out of 61 voluntary

Question 1: Consider the reaction between hydrochloric acid and egg shell.

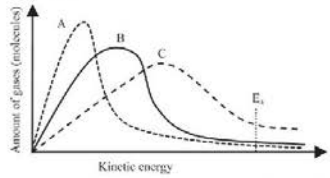
$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$



1.1 Which change will provide the result shown as Graph B?
A. Increasing the volume of HCl solution.
B. Increasing the amount of egg shell.
C. Increasing the size of egg shell fragments.

1.2 Because ......
D. It increases the activation energy (E_a).
E. It reduces the interface area between the two reactants.
F. It makes the reaction reach its equilibrium faster.

Question 2: Graphs A, B, and C shown below indicate the changes in kinetic energy of gas molecules.



2.1 Which change will occur with Graph B when the reaction temperature increases?
A. Graph B remains the same.
B. Graph B shifts to Graph A.
C. Graph B shifts to Graph C.

2.2 Because ......
D. The number of high kinetic energy molecules will increase.
E. The reaction activation energy (E_a) will decrease.
F. Bonding energy of the reactants will decrease.

Fig. 1 Examples of two-tier three choice questions (selecting choices of answer for both content question and explanation tiers).

Question 3: Consider the reaction of magnesium ribbon and sulphuric acid.

$$Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$$

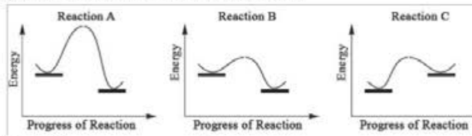
The volume of $H_2(g)$ measured from the initial to 5.00 cm^3 is shown below.

Volume (cm^3) of $H_2(g)$	1.00	2.00	3.00	4.00	5.00
Time (s)	4.00	6.00	9.00	14.00	20.00

3.1 What is the average rate of $H_2(g)$ production?
A. 0.17 cm^3/s. B. 0.25 cm^3/s. C. 0.50 cm^3/s.

3.2 Please supply your calculation method ....

Question 4: Consider reaction A, B and C below.



4.1 Which statement is correct?
A. Reaction A occurs faster than reaction B and C.
B. Reaction B and C occur faster than reaction A.
C. Reaction A, B and C occur with the same rate.

4.2 Please supply your reason or explanation for your response above.
....

Fig. 2 Examples of two-tier three choice questions (selecting choices of answer for content question tier and supply calculation method or reason for explanation tier).

students (two classrooms) who attended all of the activities throughout the study were purposively selected as the participants of this study. They were grade 11 students attending the Chiangkaew Pittayakom School, a medium-sized public high school in the Ubon Ratchathani province of Thailand.

Implementation

Prior to the implementation, the students spent an hour completing the pre-conceptual test on chemical reaction rates, also called the pre-test. They then participated in seven inquiry/analogy learning plans on chemical reaction rate for five weeks, three hours a week, totalling 15 hours. Right after the implementation, they spent an hour to completing the post-conceptual test, also called the post-test. Thirty days after the implementation, they spent another hour completing the delayed-post conceptual test, also called the retention-test. Please note that the pre-, post-, and retention-tests were the same test but the item questions and choices had been rearranged. In addition, these students were studying the topic of chemical equilibrium during the time between the post- and retention-tests. Finally, participants who provided interesting explanations in the good-, alternative-, and misconception were purposively selected for an informal interview.

Data analysis

The data collected in this study were pre-, post, and retention-conceptual scores. Each two-tier three-choice item was worth 2 points (1 point for each tier). Therefore, the available score for each test was 60 points. The test scores were also analyzed by using the paired-samples t-test to identify the differences between the means of pre- and post-conceptual test scores and between the means of post- and retention-conceptual test scores. Class normalized learning gain or $\langle g \rangle$ was applied to minimize the floor and ceiling effect. That is a student can get no less than 0% and no more than 100% correct with such an instrument. Hake (1998) explained that a student who gains a small pre-test score may have more chance of attaining a large percentage gain, while a student who begins with a large pre-test score may gain only a small percentage score. In other words, it is common for students who attain a higher pre-test score to attain a smaller absolute gain (post-test score minus pre-test score). The floor and ceiling effect can be minimized by using normalized gain $\langle g \rangle$ analysis. The topics with $\langle g \rangle \leq 0.30$, $0.30 < \langle g \rangle > 0.70$, and $\langle g \rangle \geq 0.70$ were classified into low-, medium-, and high gain categories, respectively (Hake, 1998).

The students were also categorized into good- (sound understanding, aligned to scientific consensus), alternative- (partial understanding, on the right track, but incomplete), and misconception (illogical or incorrect information, simply wrong) groups according to their answers, see categories of student conceptions in Fig. 3 (Mulford and Robinson, 2002; Çalik *et al.*, 2009a). Student answers were used as the criteria for categorizing them into groups. If the student answered correctly for both tiers, correctly for either the first or the second tier, or incorrectly for both tiers, they were categorized in the good-, alternative-, or misconception group, respectively.

Good conception	Alternative conception	Misconception
Sound understanding, all conceptions aligned to scientific consensus.	Incomplete or partial understanding, on the right track but incomplete.	No understanding, illogical or incorrect information, simply wrong.

Variety of student understanding or conceptions

Fig. 3 Levels of student conceptions compared to scientific consensus, adapted from Çalik *et al.* (2009a) and Mulford and Robinson (2002).

Results and discussion

The study results were divided into three parts: students' pre-, post-, retention–conceptual test scores, percentages of students in the good-, alternative-, and misconception categories, and students' analogies of chemical reaction rate.

Students' pre-, post-, retention-conceptual test scores

Prior to the implementation of inquiry incorporated with analogy learning plans on chemical reaction rate, the mean of the students' pre-conceptual test score was 19.70 (SD 3.10), as shown in Table 2. The students obtained high scores for the topics of the effect of catalyst and retarder (50.25%) and the effect of concentration (43.12%), while they obtained low scores for the topics of the effect of the nature of the substance (22.75%) and the surface area (26.75%), definition and calculation (23.60%) and the theories of chemical reaction rate (23.57%). The higher scores may have arisen because these students had learned about the effects of catalysts, concentration, and temperature during the basic chemistry course taught in the previous year. Right after the implementation, the mean of the students' post-conceptual test score was 45.32 (SD 6.46). The students obtained the highest post-test percentage scores and actual gains for the topics of definition and calculation (84.50 and 60.90) and the nature of substances (79.50 and 56.75). These high actual gains may have occurred because this topic is not complicated and once the students had understood the concepts and theories, they were able to calculate the chemical reaction rate. Moreover, the analogies that the instructor used in these topics (running various distances within a limited time and sailing paper boats of various thickness) were perfectly matched to the target concepts (see Table 4). The lowest post-test percentage score was in the topic of the effect of surface area (68.50%) possibly because some students found the relation between size and surface area to be confusing. The student interviews revealed that some of them had misunderstood that an object or substance with a larger size has a larger surface area, which was correct when compared one smaller object to one larger object. However, they did not notice that the amount (weight or mole) of substances must be considered. Therefore, smaller sized substances have a larger total surface area than larger sized substances when the mole numbers were equivalent. In other words, the total surface area of equal amounts of substances increases as the size is reduced (Normand and Peleg, 2014).

The normalized learning gain for the whole conceptual test was 0.64 (medium gain). The students were classified as high gain for the topics of definition and calculation of chemical

Table 4 Students' pre- and post-conceptual test scores on chemical reaction rate

Topics (score)	Conceptual test score (points)							
	Pre-			Post-			Gain	
	Mean	SD	%	Mean	SD	%	Actual	$\langle g \rangle$
1. Definition and calculation (10)	2.36	0.89	23.60	8.45	1.25	84.50	60.90	0.80
2. Theories (14)	3.30	1.34	23.57	9.93	2.04	70.93	47.36	0.62
3. Nature of substances (4)	0.91	0.96	22.75	3.18	0.66	79.50	56.75	0.73
4. Surface area (8)	2.14	0.95	26.75	5.48	1.41	68.50	41.75	0.57
5. Concentration (8)	3.45	0.82	43.12	6.57	1.56	82.21	39.09	0.69
6. Catalyst and retarder (8)	4.02	1.75	50.25	5.66	1.60	70.75	20.50	0.41
7. Temperature (8)	3.52	1.21	44.00	6.05	1.89	75.62	31.62	0.56
Total (60)	19.70	3.10	32.83	45.32	6.46	75.53	42.68	0.64

reaction rate (0.80) and the effect of the nature of substances (0.73), while the remaining topics were classified as medium gain. The students obtained the lowest normalized gain (0.41) for the topic of the effect of catalyst and retarder, possibly because this topic is complicated and abstract and they could not understand how the mechanism of a catalyst and retarder affect the reaction rate. It was concluded from the student interviews that some of them had misunderstood that a catalyst increases the energy of reactants, while a retarder decreases the energy so the catalyzed reaction proceeds at a faster rate than a normal reaction. Some misunderstood that catalysts and retarders affect the amount of exothermic or endothermic energy of the reaction. Some of them supplied the correct explanation that the catalyzed reaction proceeds at a faster rate than a normal reaction because the catalyst decreases the activation energy (E_a) of the reaction. This is consistent with the problems in learning about chemical reaction rates identified by Çalik *et al.* (2010) who identified that students lack an understanding of the effect of surface area and catalyst on the rate of reaction. In addition, the dependent samples *t*-test analysis indicated that the means of the post-conceptual test scores in every topic were statistically higher than those of the pre-test scores at the significance level of 0.05. This finding indicates that the incorporation of a combined inquiry and analogy learning approach was effective at enhancing students' conceptions of chemical reaction rate. This finding confirm that intervention of inquiry activities (Van Driel, 2002; Chairam *et al.*, 2009) and corresponding and familiar analogies (Çalık and Ayas, 2005; Çalik, *et al.*, 2010) are powerful for promoting student conceptual changes and moving to the more correct conceptions of reaction rate.

Students' retention of the concept of chemical reaction rate

Thirty days after the implementation, the retention-conceptual test was administered. The mean total score of the retention-conceptual test was 48.03 (SD 9.04). The dependent samples *t*-test analysis indicated that the retention scores in the topics of the effects of surface area, concentration, and temperature were statistically higher than those for the post-conceptual scores at the significance level of 0.05. However, no statistical difference was found for the topics of effect of the nature of substances and catalysts and retarders, definition and calculation, and theories involving chemical reaction rate, as shown in Table 5.

Since the retention scores were higher than or not less than the post-test scores, the findings indicate that there was retention of knowledge of all the topics of chemical reaction rate. The high increase of performance in the retention test compared to the post-test may have arisen because analogy instruction may be one of the effective tools for promoting student conceptual changes and then storing in their long-term memories (Çalik *et al.*, 2010). The other explanation is that during the time between the post- and retention-tests the participants were studying the topic of chemical equilibrium, which is highly related to the chemical reaction rate. In addition, the participants also had access to additional instruction and did additional homework before the retention test.

Table 5 Students' post- and retention-test scores on chemical reaction rate

Topics (score)	Post-test			Retention-test			*T*-test	
	Mean	SD	%	Mean	SD	%	*T*	Sig*
1. Definition and calculation (10)	8.45	1.25	84.50	8.55	1.27	85.50	0.46	0.65
2. Theories (14)	9.93	2.04	70.93	10.68	2.92	76.29	1.96	0.06
3. Nature of substances (4)	3.18	0.66	79.50	3.34	0.83	83.50	1.16	0.25
4. Surface area (8)	5.48	1.41	68.50	6.09	1.52	76.12	2.47	0.02*
5. Concentration (8)	6.57	1.56	82.21	7.07	1.44	88.38	2.33	0.02*
6. Catalyst and retarder (8)	5.66	1.60	70.75	6.02	2.02	75.25	1.11	0.27
7. Temperature (8)	6.05	1.89	75.62	6.55	1.58	81.88	2.67	0.01*
Total (60)	45.32	6.46	75.53	48.03	9.04	80.05	2.07	0.04*

* Statistically difference at significance level of 0.05.