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Small-Scale Inquiry-Based Experiments to Enhance High School Students' Conceptual Understanding of Electrochemistry

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Abstract. This study aimed to develop small-scale experiments of electrochemistry based on inquiry learning approach and to use the experiments to enhance students' conceptual understanding of electrochemistry especially at the molecular level. The experiments consisted of oxidation and reduction reactions, galvanic cells, cathodic protection, and batteries. The data collecting tools included 24 items of two-tier conceptual test and mental model drawings of a galvanic cell. Thirty-one Grade-12 students participated in the study. The paired samples T-test analysis revealed that the average post-experiment score (mean 30.68, SD 10.86) of conceptual test was statistically higher than the average pre-experiment score (mean 20.81, SD 10.95) at 0.05 level of significance. In addition, the average post-experiment score (mean 12.10, SD 5.49) of mental models was statistically higher than the average pre-experiment score (mean 7.69, SD 5.47) at 0.05 level of significance. Prior to performing the experiments, most students were in the *Partial Understanding with Specific Misunderstanding* (PU+MU) to *No Understanding* (NU) categories. After performing the experiments, the students' major categories moved to the more correct scientific conceptions, the *Partial Understanding* (PU) to *Partial Understanding with Specific Misunderstanding* (PU+MU). This indicated that the experiments can enhance students' conceptual understanding and mental models of electrochemistry.

Keywords: electrochemistry, small-scale experiment, molecular conceptual understanding.

1. Introduction

Almost all high school students are required to study electrochemistry in both lecture and laboratory settings. Many students revealed that electrochemistry is one of the difficult chemistry topics. In addition, some students may hold alternative conceptions – conceptions that are not consistent with the consensus of scientific community, which may be partially right, but incomplete, or just simply wrong [1] – about the electrochemistry. Requiring students to draw and explain molecular representations of the some electrochemistry experiments, such as reaction in galvanic cells may to reveal their understandings and identify some of their alternative conceptions.

1.1. Roles of mental models in learning chemistry

Mental models are representations of objects, ideas, thinking, or processes which individuals intrinsically construct during cognitive functioning [2], [3]. People use these models to reason, describe, explain, and/or predict scientific phenomena (processes or systems). Mental models can be generated in various formats to communicate ideas to other people or to solve problems [2], [3], and can represent either physical entities via verbal descriptions, diagrams, simulations, and concrete models, or conceptual understanding, such as models of ideas, thinking, or intangible concepts [4]. If their mental model fails to assimilate new

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experiences, students may modify their existing models or generate alternative models [5]. Mental models are considered as an important part of learners' conceptual frameworks [5] and they play a potential role in learning chemistry at the molecular level, because much of chemistry involved at this level and cannot access to direct perception [6]. Full understanding of chemical processes involves the ability to connect events at a macroscopic level with events at the molecular level [7]. Therefore, students need to transform these invisible events or phenomena into equivalent mental (or conceptual) models or representations which is difficult for many students [8],[9],[10].

1.2. Three levels of representations in chemistry

Representations in chemistry, also called chemical representations, refer to various types of formulas, structures, and symbols used to represent chemical processes and conceptual entities, such molecules and atoms. They can be viewed as metaphors, models, and theoretical constructs of chemists' interpretation of nature and reality [11]. Previous research highlighted three levels of representations in chemistry as follows [7],[12].

1) Macroscopic representation. This describes bulk properties of tangible and visible phenomena in the everyday experiences of learners when observing changes in the properties of matter, such as color changes, formation of gases, and precipitates in chemical reactions.

2) Microscopic Representation. This is also called sub-microscopic or molecular representation, provides explanations at the particulate level in which matter is composed of atoms, molecules and ions.

3) Symbolic Representation. This involves the use of chemical symbols, formulas, and equations, as well as molecular structure drawings, diagrams, and models to symbolize matter. It can provide information for both macroscopic (relative amounts or moles of involved substances) and molecular levels (numbers of formula unit of involved substances).

Students' conceptual understandings of electrochemistry can be investigated by using conceptual test and by drawing mental models of electrochemistry. The information about students' conceptual understanding before and after performing experiments and learning in lecture classes can be used in the design of animations with molecular features to best support students' acquisition in learning electrochemistry especially what happens at the molecular level.

2. Research Purpose and Objectives

The primary purpose of this study was to explore students' conceptual understanding of electrochemistry by using conceptual test and mental model drawings prior to and after performing corresponding experiments. The research objectives were:

1) To compare students' conceptual understanding scores before and after they performed corresponding experiments when assessed by the conceptual test and mental model drawing of electrochemistry.

2) To categorize students' conceptual understanding regarding their explanations in the conceptual test and their mental models of electrochemistry before and after they performed corresponding experiments.

3. Methodology

This one-group pre-test post-test study used a "mixed methods" design [13] that incorporated both qualitative and quantitative methods as its research paradigm.

3.1. Participants

With permission from the course instructors, 31 Grade-12 students in the Gifted in Science classroom at Satrisiriket School in Srisaket Province in the first semester of academic year 2014 participated in this study.

3.2. Research tools

Two types of research tools were used in this study, treatment and data collection tools. The treatment tools consisted of four small-scale experiments based on the inquiry learning approach, oxidation and reduction reactions, galvanic cells, cathodic protection, and connecting batteries in series. The two data collecting tools were a conceptual test of electrochemistry containing 24 items of two-tier three-choice test in which students were required to make their choices of answers in the first tier, and then provide their explanations for those choices, and mental model drawings of galvanic cells in which students were asked to draw their understandings of what happens at a molecular or particulate level in provided galvanic cells ($Zn|Zn^{2+}||Cu|Cu^{2+}$, $Zn|Zn^{2+}||Ni|Ni^{2+}$, or $Ni|Ni^{2+}||Cu|Cu^{2+}$) as shown in Fig. 1.

3.3. Implementation

The participants were requested to complete conceptual test of electrochemistry and mental model drawings of galvanic cells before participating in (four small-scale experiments of electrochemistry over a period of nine hours (three hours a week). After this period, they were asked to complete a conceptual test of electrochemistry and mental model drawings again.

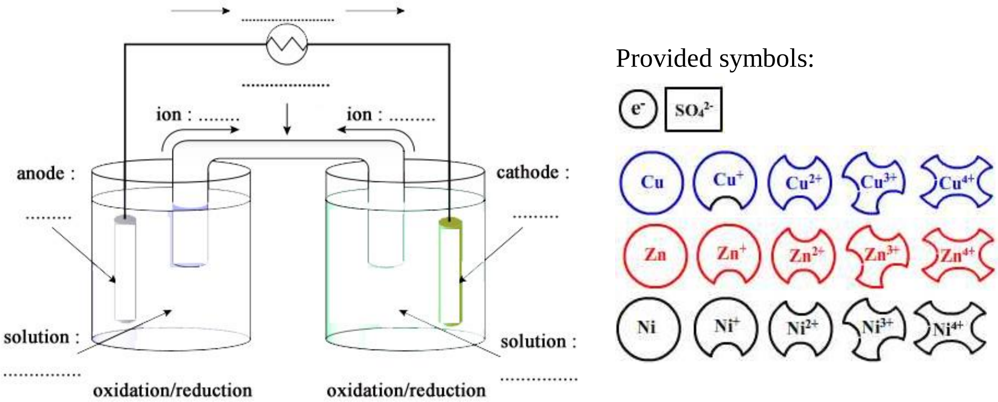

Fig. 1: Mental model drawing for a given galvanic cell ($Zn|Zn^{2+}||Cu|Cu^{2+}$, $Zn|Zn^{2+}||Ni|Ni^{2+}$, or $Ni|Ni^{2+}||Cu|Cu^{2+}$).

3.4. Data analysis

The data collected in this study were analyzed as follows:

1) Conceptual tests: The pre- and post-conceptual test answers were awarded 1 and 0 point for correct and incorrect choices respectively in the first tier. The explanations provided in the second tier were awarded 0, 0.25, 0.5, 0.75, or 1 point for their conceptual understandings (possible total score for each item was 3 points). Students' explanations were categorized into five groups as follows [14]:

- Explanations with all concepts corresponding to both scientific consensus and scientific concepts of scientists scored 1 point and were defined as "Sound Understanding: SU".
- Explanations with at least one concept corresponding to scientific consensus and scientific concepts of scientists scored 0.75 point and were defined as "Partial Understanding: PU".
- Explanations with at least one concept corresponding to scientific consensus and scientific concepts of scientists but partially alternate to scientific concepts scored 0.5 point and were defined as "Partial Understanding with Specific Misunderstanding: PU+MU".
- Explanations with no concept corresponding to scientific consensus and scientific concepts of scientists scored 0.25 point and were defined as "Specific Misunderstanding: MU".
- Explanations with no detail or no scientific concepts scored 0 point and were defined as "No Understanding: NU".

2) Mental model drawings: The pre- and post-mental model drawings were scored by using a rubric developed by the authors. These models were also categorized into five groups in the same ways as the explanations in the conceptual tests. The available score was 18 points, 6 points for the macroscopic features and labelling and 12 points for the macroscopic features.

3) Students' scores from pre- and post-conceptual tests and mental model drawings were analysed by the use of paired-samples T-test.

4. Results and Discussion

There were two main sections of results in this study: 1) students' scores of conceptual test and mental model drawings of electrochemistry, and 2) conceptual categories of electrochemistry.

4.1. Students' scores in the conceptual tests and mental model drawings

There were two types of scores in this study, those for the conceptual tests and those for the mental model drawings.

Students' pre-conceptual test scores for the means of the first and second tiers and the totals were 12.29, 8.52, and 20.81, respectively (Table 1). After the completion of the four small-scale experiments, the means of the post-test scores were 16.35, 14.32, and 30.68, respectively. The gains in the conceptual scores were 4.06, 5.81, and 9.87 respectively. The paired-samples T-test analysis indicated that these differences between means of the pre- and post-conceptual tests were statistically significant in all cases. The percentage for the means of the pre-test scores for the first tier choices (51.21%) was much higher than that for the second tier explanation parts (35.48%). After the experiments, the percentage for the mean of the post-test score in the choice part (68.15%) was still higher than that for the second tier explanation part (59.68%). This situation arose because sometimes the students knew the answers without complete scientific conceptual explanation. As a result, they were able to provide partial-, alternative-, or misunderstandings for their answers [14]. These improvements in the percentages of the post-test scores indicated that these small-scale experiments of electrochemistry were effective in the enhancement of the students' conceptual understandings.

Table 1: Students' scores assessed by using conceptual test of electrochemistry and mental model drawings

Test	Test score										T-test	
	Avai-lable	Pre-test			Post-test			Change				
		mean	SD	%	mean	SD	%	mean	SD	%	T	p
Conceptual test	**48**	**20.81**	**10.95**	**43.35**	**30.68**	**10.86**	**63.91**	**9.87**	**2.47**	**20.56**	**22.22**	**0.00***
Choice (1st tier)	24	12.29	4.47	51.21	16.35	4.30	68.15	4.06	1.82	16.94	12.40	0.00*
Explanation (2nd tier)	24	8.52	6.71	35.48	14.32	6.87	59.68	5.81	1.89	24.19	17.13	0.00*
Mental model drawings	**18**	**7.69**	**5.47**	**42.74**	**12.10**	**5.49**	**67.20**	**4.40**	**2.08**	**24.46**	**11.77**	**0.00***
Macroscopic feature	6	3.05	1.71	50.81	4.06	1.78	67.74	1.02	0.71	16.94	7.94	0.00*
Molecular feature	12	4.65	3.86	38.71	8.03	3.75	66.94	3.39	1.69	28.23	11.18	0.00*
Total	**66**	**28.50**	**16.33**	**43.18**	**42.77**	**16.15**	**64.81**	**14.27**	**3.53**	**21.63**	**22.79**	**0.00***

* Statistical differences when performed by paired-samples T-test at 0.05 level of significance.

For the mental model drawings of galvanic cells, the students' mean pre-drawing scores in macroscopic (and labeling) features, molecular (or microscopic) features, and totals were 3.05, 4.65, and 7.69 respectively and the mean post-drawing scores were 4.06, 8.03, and 12.10 respectively. The post-drawing gains in the mental model scores were 1.02, 3.39, and 4.40 respectively. 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 the pre-mental model score of 50.81% for macroscopic features, much higher than the 38.71% for molecular features. An explanation of this may be that students find molecular features difficult to understand due to their intangibility and/or invisibility [4]. However, after involvement in the experiments, the students' percentage increase in the mean post-mental model score regarding molecular features was 66.94%. This improvement of 28.23% compared to the 38.71% for the pre-test indicated that the small-scale experiments of electrochemistry were effective in the enhancement of the students' mental models at the molecular level. Although the students obtained mean post-test scores significantly higher than the mean pre-test scores for conceptual tests and mental model drawings, these gains were not as high as they should be.

4.2. Students' conceptual categories in regard of electrochemistry

The students were categorized into five groups regarding their explanations in the conceptual tests and information expressed in their mental model drawings. Prior to their involvement in the four small-scale experiments of electrochemistry, their explanations were categorized mostly in PU+MU (32.26%), MU (25.81%), and NU (25.81%) as shown in Table 2. After the experiments and as a result of their post-conceptual test explanations the students moved to the more correct conceptual understanding categories of

PU (29.03%), PU+MU (25.82%), and MU (22.58%). When asked to draw mental models of how they understand what happens at the molecular level in galvanic cells, the categorisation of the students' macroscopic information at the pre-stage fell mostly in PU (35.48%), MU (25.81%), and PU+MU (22.58%), and their molecular information for the same stage was categorized mostly in MU (29.03%), NU (25.81%), and PU (22.58%). After the experiments, their models moved to more correct conceptual understanding categories. For macroscopic information, most were in SU (32.26%), PU (29.03%), and PU+MU (19.35%), and for molecular information, most were categorised in SU (35.48%) and PU (22.58%).

Table 2: Frequencies and percentages of students in the five conceptual categories

Frequencies (f) and %		**Pre-test**					**Post-test**				
		SU	**PU**	**PU+MU**	**MU**	**NU**	**SU**	**PU**	**PU+MU**	**MU**	**NU**
Conceptual tests : Explanation part	f	1	4	10	8	8	6	9	8	7	1
	%	3.23	12.90	32.26	25.81	25.81	19.35	29.03	25.81	22.58	3.23
Mental models: Macroscopic feature	f	2	11	7	8	3	10	9	6	5	1
	%	6.45	35.48	22.58	25.81	9.68	32.26	29.03	19.35	16.13	3.23
Mental models: Molecular feature	f	2	7	5	9	8	11	7	6	6	1
	%	6.45	22.58	16.13	29.03	25.81	35.48	22.58	19.35	19.35	3.23

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 observations of the experiments, leading to modification of their mental models to provide more reasonable explanations of what happens at the molecular level of given galvanic cells. However, some students' modified models may still contain misconceptions [1].

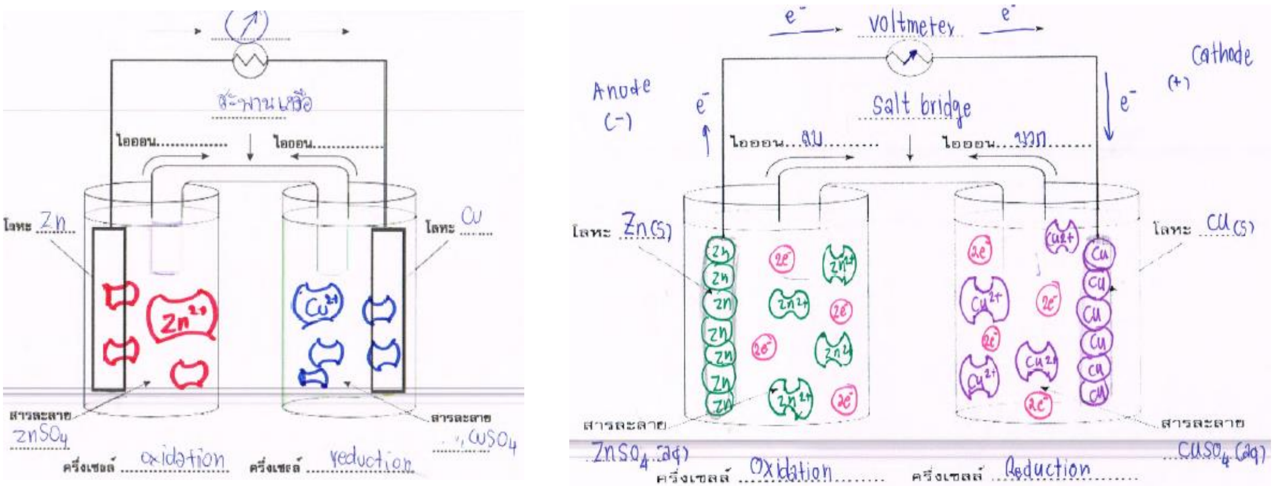

Fig. 2: Examples of students' pre- (left) and post-Mental model drawing (right) for a given galvanic cell.

5. Conclusion and Implications

The study results indicated that the small-scale experiments of electrochemistry based on inquiry learning approach was effective to enhance students' conceptual understanding and mental models of corresponding concepts. The students' obtained the post-conceptual test score statistically higher than the pre-test score. In addition, their post-mental model score was statistically higher than the pre-model score. The majorities of the pre-experiment scores were from the choice part of the conceptual test and from the macroscopic part of the mental models. However, after performing corresponding experiments, their post-experiment scores in the explanation part of the conceptual test and in the molecular part of the mental models played more important role than in the pre-experimental scores. Prior to performing corresponding experiments, the majority of students were in the partial understanding with specific misunderstanding

(PU+MU) to no understanding (NU) categories. After performing the experiments, the majority them moved to the partial understanding (PU) to partial understanding with specific misunderstanding (PU+MU) categories, which were better scientific conceptions. This indicated that the corresponding experiments can enhance students' conceptual understanding and mental models of electrochemistry.

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 might consider using a simulation, animation, or other visualization tools to help students visualize concepts at the molecular level and then connect these concepts to the corresponding macroscopic procedure or features. As a result, students may achieve a complete and lasting conceptual understanding [10]. Students' mental models of a specific process contain rich relevant information that can be used in designing an animation or simulation to support students' acquisition or mental model [15].

6. Further Study

The information about students' conceptual understanding of electrochemistry and mental models of galvanic cells will be used in the design of a molecular animation to support students' understanding of electrochemistry. 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. Alternative conceptions prior to and after the implementation will be indentified.

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