CONNECTIONS INVOLVING THE USE OF CHEMICAL LANGUAGE AND UNDERSTANDING OF REDUCTION-OXIDATION REACTION

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Abstract

Understanding submicroscopic level, which requires in-depth chemistry knowledge, is difficult for students. The sample of the research consisted of 32 students, who performed a teaching-learning sequence of two electrochemical reactions. Eight of them were videotaped and their speech was transcribed and analyzed. The results indicated that students who used more chemical terms improved their understanding of the submicroscopic level. Talking more, in this case, showed no relation to learning directed to an instrumental understanding (focus on how). The use of more chemical terms enabled them to grasp a relational understanding (focus on why) and the predictive ability of new chemical phenomena.
Keywords: *chemical education, chemical terms, electrochemistry, relational understanding, submicroscopic level.*

Introduction

To comprehend how scientific knowledge is inserted in the classroom environment, Bybee (1995) created three categories of scientific literacy named: functional, conceptual/procedural, and multidimensional. The concern was to comprehend how scientific concepts were examined and understood in the classroom environment. The functional category, specifically, encompasses vocabulary that is proper to the sciences, that is, the specific chemical language used. According to Bybee (1995), to learn science students must develop the ability to read and write within this perspective. In this research, the term *chemical language* refers to the vocabulary used by students while developing an activity to understand chemical reactions. Subsequently, such language terms will be better detailed.

Chemistry comprehension involves three representational levels: macroscopic, representational and submicroscopic (Johnstone, 1993) being the last one the focus of this research. Gilbert and Treagust (2009) carried out a research where they considered the various denominations used by different researchers in several studies, when referring to these representational levels. To consider a denomination that was as simple as possible and that could constitute meaning, they proposed the terms macro (instead of macroscopic), symbolic and submicro (as an alternative for submicroscopic) and, consequently, these terms were chosen in this research. Another interesting point is that there has been no unanimous definition for what is understood by each of these levels. Then, a definition was proposed for each representational level according to Gilbert and Treagust (2009).

Gilbert and Treagust (2009) have believed that the macro level refers to perceptible properties, both in the laboratory and in everyday life. To explain what is being visualized, chemists have used the submicro level, because „in chemistry, it is usual to produce models built from entities such as atoms, ions, molecules and free radicals ...“ (Gilbert & Treagust, 2009, p.4). Finally, the symbolic level „involves the allocation of symbols to represent atoms, whether of one element or of linked groups of several elements“ (Gilbert & Treagust, 2009, p.4). In this specific case, the equations that represent, symbolically, the two chemical reactions studied by the students were considered.

Cheng and Gilbert (2009) have argued that an obstacle to learning chemistry may be related to the difficulty in changing among the three levels and they point out that, to better associate the various forms of representation, the visual mode should also be explored. Such argument was considered in the electrochemical teaching-learning sequence proposed in this research.

Treagust, Chittleborough and Mamiala (2003) conducted a survey with high school students in which, from an observable phenomenon, they researched the explanations produced by these students at the symbolic and submicro levels. The results showed that teachers and students may interpret these representations differently, which may hinder students‘ learning (Treagust, Chittleborough, & Mamiala, 2003). Therefore, as such concepts are difficult for students to understand, it is necessary to encompass representations at the symbolic and submicro levels during the teaching-learning process to improve the mastery of chemistry concepts. Specifically, regarding the submicro level, the nature of chemistry itself is essentially molecular, thus, it is fundamental that chemistry teaching considers the submicroscopic comprehension of the phenomena (Taber, 2013).

It is important to highlight that chemical language is peculiar and involves a level of detail of difficult access to students. For example, talking about a symbolic concept or representation of chemistry will not be enough for students to appropriate this terminology. On the contrary, it is necessary to restate such explanation several times so each student can recreate meaning, at his or her own time and manner, acquiring meaningfully proficiency, using the language appropriately in each context used, making learning meaningful. Thus, the student could be able to predict what happens in other similar but different situations.

Regarding students’ comprehension, Treagust, Chittleborough and Mamiala (2003) have referred to two levels of understanding, whose difference is in their depth, namely instrumental and relational. Instrumental level refers to „knowing how“ (p.1353), which seeks a more mechanical learning (Skemp, 1976). As for the relational level, the students demonstrate the reason why they are doing something (Skemp, 1976), what Treagust, Chittleborough and Mamiala (2003, p.1353) named “knowing why”. This latter type may result in an appropriate understanding of the chemical concepts involved in a particular phenomenon studied. For example, a student may know how to calculate the oxidation number of all atoms and ions involved in a chemical (instrumental understanding) reaction but may fail to understand why these oxidation numbers vary and what that means (relational understanding).

Treagust, Chittleborough and Mamiala (2004) have also investigated the students‘ understanding of the descriptive and predictive nature of the teaching model used. The results indicated that most students were able to understand the descriptive nature of the teaching model, but the same did not happen in relation to the predictive model, which would involve using the model to make and test predictions. The analyzed students presented limitations on the predictive nature of the models.

The aim of this research was to understand the difference in the process of four groups (Eight students of a total sample of 32) when performing a chemistry activity, involving basic concepts of electrochemistry. Half of them demonstrated the capacity to change from the symbolic to the submicro level (namely the transition group) while the other half did not manage to do so (no transition group). This research has questioned whether these positive and negative results could have arisen from the quality of the discussion. Therefore, the research question is:

During group discussions, how to talk more or use chemical terms helped to elaborate and reformulate ideas about the symbolic and submicro levels?

From this, the focus of the research was to find answers to the following question: Is there a connection involving instrumental/ relational understanding, or even with a prediction stemming from a teaching model?

Methodology of Research

General Background of the Research

This research is part of a broader qualitative work, whose objective was to comprehend how students think and rethink chemical concepts based on the use of images, from an intense metavisual[1] process considering the representational levels. The topic chosen for this research was the understanding of initial concepts in electrochemistry, using two chemical reactions. The first one was between solid iron and aqueous solution of copper (II) sulfate and the reaction was between solid iron and aqueous solution of sulfuric acid. During the activity, students were supposed to propose explanatory models at the symbolic and submicro levels. Groups were classified as - no transition, partial transition or transition - depending on whether they showed signs of transition between the symbolic and submicro levels or not, according to the criteria established in Locatelli's (2016) research, as seen in Table 1:

Table 1. Classification of the 16 groups (Locatelli, 2016, p, 203, adapted).

	No transition	**Partial transition**	**Transition**
Original Groups	2, 5, 7, 9, 11 and 12	1, 3, 4, 6, 8 and 16	10, 13, 14 and 15
Groups chosen for this research	2 and 5	None	10 and 14
Renamed groups for this research	**1 and 2**	None	**3 and 4**

To form this research, two non-transition groups (1 and 2) and two transition groups (3 and 4) were randomly chosen for analysis.

1 According to Gilbert (2005), metavisualization is the metacognition of visualizations.

Sample of Research

Eight students aged 16 to 17 enrolled in a private high school in Sao Paulo (Brazil) participated in this research. Initially, 32 students (16 pairs) participated in the proposed research activity, however, 8 students (4 pairs) were randomly selected for this research, so the data could be analyzed in greater depth and within the perspective mentioned above - transition groups (3 and 4) and non-transition groups (1 and 2). Participants were informed about the research and, voluntarily, they agreed to take part in it.

Instrument and Procedures

The students performed a teaching-learning sequence referring to basic concepts in electrochemistry, being the activity videotaped for further analyses. They were asked to propose explanations for the submicro level of chemical reactions between solid iron and copper and hydrogen ions. These discussions were transcribed, in order to verify how far the amount (talking more) or the quality of words (use of chemical terms) contributes to achieving good results. Two of 11 speech excerpts were chosen to exemplify and to count the number of words and chemical terms used during the discussion. These excerpts correspond to the elaboration and reformulation of the submicro level for the chemical reactions between the solid iron and the solution of copper (II) sulfate and between the solid iron and sulfuric acid solution.

Data Analysis

Firstly, Microsoft Word Count was used to determine the quantity of words from such passages. Secondly, to quantify the chemical terms, Guedes‘s (1992) proposal was chosen, selecting categories 1, 2 and 4 (total of 7) from his work, respectively related to chemical terms, as explained and exemplified in Table 2:

Table 2. Categories and examples.

Original Category (Guedes (1992)	Renamed category for this research	Category’s name	Example
1	1	Structural	Atom or electron
2	2	Specific	Iron or copper ion
4	3	Group of constituents	Sulfate or acid

These three categories were chosen because they constitute a specific language in Chemistry. The analysis was carried out within the category proposed by Guedes (1992) and it was validated by three components of distinct research groups that did not participate in this research. No differences were found in such classification made by them.

Subsequently, transition and no transition groups were compared, searching for similarities and differences regarding the quantity of words and the amount of chemical terms used.

Research Results

Amount of Words x Chemical Terms

The quantity of words spoken by each group is showed in figure 1:

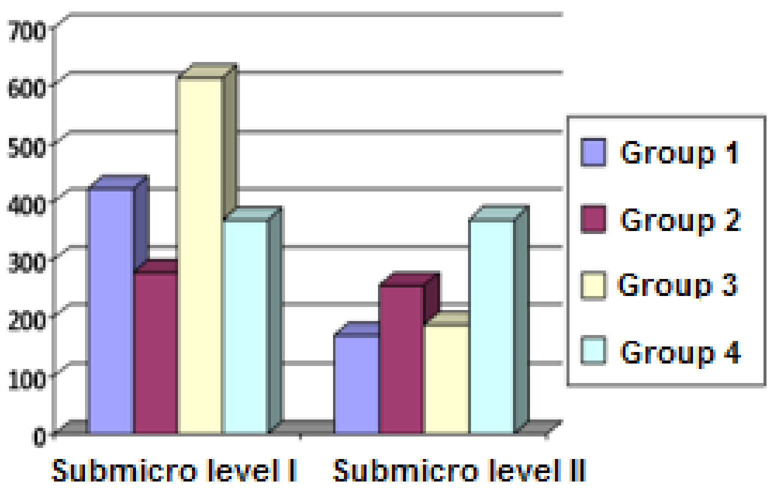

Figure 1. Amount of words – no transition groups (1 and 2) x transition groups (3 and 4).

As can be seen in figure 1, there is no relationship between a larger quantity of words and better performance. For example, although group 1 spoke more than group 4 in the submicro level I, students did not achieve a better result. The same was observed with the performance of groups 2 and 3 in the submicro level II. These results indicated that simply talking more do not necessarily lead to good results.

The amount of chemical terms used by students in the dialogues is showed in figure 2:

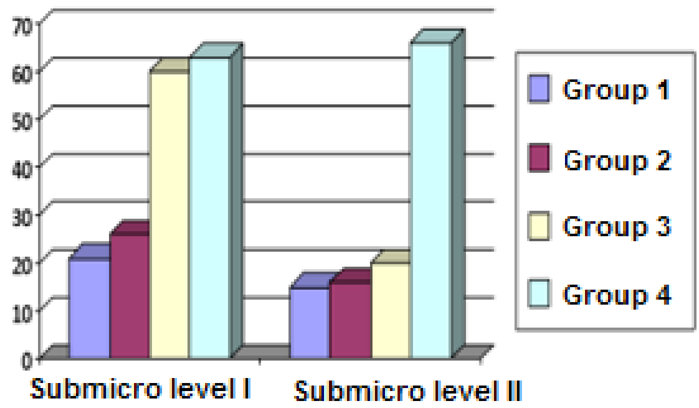

Figure 2. Amount of chemical terms – no transition groups x transition groups.

By analyzing the overall results of figure 2, it was possible to infer that transition groups 3 and 4 used a greater amount of chemical terms to elaborate and reformulate explanatory models in the submicro level than no transition groups 1 and 2. These results indicated a relational understanding of the chemical reactions, where the students developed more in-depth discussions.

Instrumental x Relational Reasoning

To exemplify the instrumental and relational reasoning demonstrated by the groups and their connection with the chemical language used, some excerpts from students' speech were transcribed while proposing explanatory models for the submicro level II. The analysis focused on group 2 (no transition group) and group 4 (transition group).

In Table 3, an excerpt was transcribed from a discussion of group 2 when they were studying the chemical reaction between solid iron and aqueous solution of sulfuric acid as follows:

Table 3. Speech excerpt from group 2, categories and chemical terms.

Students' speech	Categories and chemical terms		
	1	2	3
B2: Let's work on the caption. Fe, being ball with x, several balls x, H.	-	Fe and H	-
A2: I'll only mark 4 balls because I did several of them before. Does it only make H or does it make HSO_4? We must write it with SO_4 to be complete, right?	-	H	HSO_4- and SO_4-
B2: I think it's just H.	-	H	-
A2: Only H or HSO_4?	-	H	HSO_4
B2: Look at the reaction here! We must draw the reaction.	-	-	-
A2: So, it's just H, then ... and H is the ball with nothing ...	-	H	-

B2: No, we already have a ball with nothing, H is a ball with a square inside it.	-	H	-
SUBTOTAL OF CHEMICAL TERMS	0	8	3
TOTAL OF CHEMICAL TERMS	11		

Group 2 demonstrated a superficial discussion. Students referred to atoms and ions as balls, and they seem to know how to *do them (instrumental knowledge)*, but they do not demonstrate an understanding as to *why* (*relational knowledge*) they are doing such thing. Therefore, they cannot propose an explanatory model for solving the chemical reaction. The use of chemical terms (11 in this interval) is restricted and apparently random, the reasoning does not progress aiming the understanding of the phenomenon observed, evidencing mechanical learning, which characterizes instrumental reasoning.

Following that, in table 4, we have transcribed an excerpt from group 4 with approximately the same time interval as before while they were having the same discussion of the submicroscopic experiment II:

Table 4. Speech excerpt from group 4, categories and chemical terms.

Students' speech	Categories and chemical terms		
	1	2	3
A4: Exactly, as it is said here in the caption ... there is the iron atom without charge and there is the iron ion ... there is the $H^{\pm}$ and there's the H ... ah ... I think the H atoms are stable after gaining electrons, they will not need to bind to anyone, so they will not bind to these iron atoms. Does it make any sense?	atom, charge, ion, atoms, elec-trons and atoms	iron, iron, $H^{\pm}$, H, H and iron	-
B4: Yeah, now at the end of the reaction there won't be more hydro-gen missing electron, so it won't bind to anyone to stabilize it.	elec-tron	hydrogen	-
A4: Exactly ... I think that's it, so in this, the reaction would have all the iron, all stable, uncharged, and the $H^{\pm}$ ions. Also, the sulfate, but sulfate does not matter in the reaction. In the end, a part of the iron will remain stable, and some irons, those that transferred electrons to hydrogen, will be free, with less negative charges and the hydrogen that was positive will be neutral (stable). ... so ... um ... but the hydro-gen for what I remember is never alone ...	charge, ions, elec-trons and charges	iron, H +, iron, iron, hy-drogen, hydrogen and hy-drogen	sulfate and sulfate
B4: Yeah, and then the hydrogens will bind to themselves and turn into H_2.	-	hydrogen and H_2	-
SUBTOTAL OF CHEMICAL TERMS	11	16	2
TOTAL OF CHEMICAL TERMS	29		

Now, group 4 demonstrates a relational discussion, as students begin to relate the ideas, *knowing why* and form a reasoning that leads them to understand the chemical reaction between iron atoms and hydrogen ions in aqueous solution. The use of chemical terms (29 in this interval) is much larger than with the other group, which helped students to elaborate a more adequate explanatory model for the chemical reaction under study.

Predictive Nature of a Chemical Reaction

The aim of this analysis was to observe how non-transition and transition groups would predict what would happen in experiment II, between solid iron and aqueous solution of sulfuric acid.

At this point of prediction, they had already reflected upon experiment I (the chemical reaction between solid iron and aqueous solution of copper (II) sulfate) which means that they had already rethought their ideas. The expectation was that if they had understood the first experiment, they would be able to predict the second one, as the latter was based on the same chemical concepts, also involving a reduction-oxidation reaction between atoms and cations. The difference in this second experiment was that there was formation of a gas and not a solid as in the previous one. This was purposefully chosen to avoid mechanical learning, focusing on the conceptual understanding of the chemical transformations involved.

Students from groups 1 and 2 failed to predict what would happen, concluding that a chemical reaction would occur, without developing an explanation as to how, as it can be observed in the speech of table 5:

Table 5. Speech excerpt from students in non-transition groups.

Group	Stu-dent	Speech
1	B1	Yeah, but do we think it will react or not? Will it react?
	A1	It will react.
2	A2	Yeah, I guess it will not go away like that (referring to the steel wool) ... there will be a little bit left but it‘s going to ... it‘s going to react, maybe ... corrode a little, anyway..

On the other hand, groups 3 and 4 were able to predict what would happen, and despite the limited speech excerpt sample, a more appropriate use of chemical terms can be observed, as shown in figure 2. The speech of a student from group 3 is presented in table 6 below, concluding the idea about what would happen with experiment II:

Table 6. Speech excerpt from students in transition groups.

Group	Stu-dent	Speech
3	B3	Yes, the appearance of a **gas**, but it will not be visible because it is **hydrogen**, **hydrogen gas** is not visible, but there will probably be bubbles ...
4	A4	That's right, then **iron** will transfer one **electron** to each **hydrogen**.
	B4	Will it **oxidize** in the same way?
	A4	Yes, the **oxidation** should be the same.

Group 3 can predict the formation of the hydrogen gas, evidencing their understanding of the previous experiment by extrapolating it to another phenomenon.

Similarly, group 4 also thinks that a reduction-oxidation reaction with electron transfer will occur. However, there is no evidence that they can predict that the hydrogen gas would be formed.

Therefore, it can be noticed that no transition groups failed to draw a prediction, whereas transition groups achieved this goal.

Discussion

According to Locatelli (2016), transition groups 3 and 4 demonstrated the ability to change between the symbolic and submicro levels, while no transition groups 1 and 2 failed to provide such ability. Considering that all groups were given the same amount of time to perform the whole activity, the question to be investigated was why some groups discussed about the task and achieved good results while others did not manage to do so? As the time factor was the same, the hypothesis was that the quality of the discussions could have been a determining factor on the positive results.

Results from figure 2 provide evidence that the quality of the discussion can play an important role on students' achievement of good results. As reinforced by Bybee (1995), not only students need to know sciences' vocabulary but also how to use it properly. By doing so, chemical language can help students to develop a relational reasoning. According to Treagust, Chitteborough and Mamiala (2003) students can only relate and interconnect the macro, submicro and symbolic levels when they develop a relational understanding of these concepts, which was observed in transition groups from table 4. These researchers have emphasized the need of using, at the same time, the symbolic and submicro levels for proper chemical understanding of the phenomenon.

By contrast, students from no transition groups, who demonstrated an instrumental understanding, did not achieve good results (Table 3). Cheng and Gilbert (2009, p.58) have believed that „... some students might rote-learn chemistry content knowledge and hence are not able to answer questions which demand deeper understanding. They might not have been familiar with or are not able to mentally change between different modes of representation."

Another aspect also brought up in Treagust, Chittleborough and Mamiala's research (2003) is that students do not always understand the representations proposed by the teacher. This may also have happened in this research, as the teacher proposed some images for students to rethink their ideas without previously discussing with them. Therefore, students might have assumed meanings that were not scientifically correct, which may have been an obstacle to overcome for groups 1 and 2 at that time.

In such case, it was possible to observe that no transition groups demonstrated discrete representations of the representational levels, which did not allow them to understand properly the electrochemical phenomena. The explanatory model of the submicro level requires an abstract and therefore difficult thinking (Al-Balushi, 2013), with an accurate use of chemical language. Thus, this research has insisted that a more precise use of chemical terms becomes fundamental to the achievement of good results, which may explain, in part, the advancement of transition groups.

Regarding the predictive nature of the reactions, it was observed that groups 1 and 2 demonstrated limited predictive capacity on the phenomena, which was the same observation pointed out in the research of Treagust, Chitteborough and Mamiala (2004). This limited predictive capacity was observed with these students who, even after elaborating and reformulating a similar chemical experiment, could not predict another similar one. On the other hand, students from groups 3 and 4 were prepared for this new task, using various chemical terms and demonstrating again a relational understanding (the why).

All these observations lead to a possible association that the use of more chemical terms by students can lead to relational understanding and help develop the ability to predict new similar chemical phenomena in new contexts, which could indicate true learning.

Conclusions

The results of this research pointed out that students should use chemical terms in their discussions in order to elaborate and reformulate chemistry concepts related to the submicro level. This stems from the fact that the submicro level is very abstract and uses a very specific chemical language. Therefore, to be able to change in this context, it is necessary to use this language fluently. By doing so, students can develop a relational reasoning (the why) rather than an instrumental one (the how), which implies a true understanding of chemical concepts. Discussing more (talking more) does not necessarily lead to good results, precisely for the reasons presented throughout this research. Although other factors are possibly involved in these reformulations, this research could verify that qualified use of chemical terms, which composes functional scientific literacy, may have contributed for the achievement of students' good results and promoted the predictive ability of other chemical phenomena. Further studies are suggested seeking to establish connections between the chemical language used by the students, instrumental and relational understandings, predictive ability and the results obtained by students, which may lead to better learning in the Chemistry area. Finally, the data obtained in this research have indicated guidelines for classroom instruction, in which it is suggested that teachers should consider all the questions explained in this article for better student learning.

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References

Al-Balushi, S. M. (2013). The effect of different textual narrations on students' explanations at the submicroscopic level in chemistry. *Eurasia Journal of Mathematics, Science & Technology Education*, *9* (1), 3-10.

Bybee, R.W. (1995). Achieving scientific literacy. *The Science Teacher, 62* (7), 28-33.

Cheng, M., & Gilbert J. K. (2009). Towards a better utilization of diagrams in research into the use of representative levels in chemical education. In: Gilbert, J. K. & Treagust, D. F. (Eds). *Multiple representations in Chemical Education* (Vol.4, p. 55-73). Springer.

Gilbert, J K. (2005). Visualization: A Metacognitive Skill in Science and Science Education. In Gilbert, J.K (Ed.). *Visualization in science education* (Vol.1, p. 9–27). Dordrecht, Netherlands.

Gilbert J.K., & Treagust, D.F. (2009). Introduction: Macro, submicro and symbolic representations and the relationship between them: Key models in chemical education. In: Gilbert, J. K. & Treagust, D. F. (Eds)., *Multiple representations in Chemical Education* (Vol.4, p. 1-8). Springer.

Guedes, M. F. (1992). Análise de conteúdo de livros didáticos de Ciências: os termos químicos apresentados e suas representações possíveis [Content analysis of science textbooks: The chemical terms presented and their possible representations]. Dissertação – Faculdade de Educação, Universidade de São Paulo, São Paulo, 209 p.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to a changing demand. *Journal of Chemical Education*, *70* (9), 701-705.

Locatelli, S. W. (2016). Relação existente entre metavisualização e as representações simbólica e submicro na elaboração de atividade em química [Relationship between metavisualization and the symbolic and submicro representations in the elaboration of activity in chemistry]. Tese (Doutorado em Ensino de Química) Universidade de São Paulo, São Paulo.

Skemp, R. R. (1976). Relational understanding and instrumental understanding. *Mathematics Teaching*, *77*, 20-26.

Taber, K. S. (2013). Revisiting the chemistry triplete: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14* (2), 156-168.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25* (11), 1353-1368.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2004). Students' Understanding of the Descriptive and Predictive Nature of Teaching Models in Organic Chemistry. *Research in Science Education, 34*, 1–20.

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