Representational competence of secondary chemistry students in understanding selected chemical principles

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ABSTRACT
Assessing students' understanding in the microscopic level of an abstract subject like chemistry poses a challenge to teachers. However, recent findings revealed that representations serve as essential avenues of measuring the extent of understanding in the disciplinal content as alternative to traditional assessment methods. Thus, this study explored the representational competencies of high school students in understanding selected chemical principles and correlated these with chemistry academic profile. The common misconceptions on the selected chemistry principles based on student' representations and their understanding of the role of chemical representations in learning were studied. Utilizing the task instrument and a scoring guide, results revealed that most students have symbolic level representational competence in selected chemical principles. Alternative misrepresentations were most observed on the students' representations in chemical bonding and in chemical equation. These misrepresentations paved the way for remediating concepts and skills in the particular topics. Furthermore, students' academic achievement and their representational competence is significantly associated and students' views in chemical representations questionnaire suggested their mental models. Moreover, students confirmed greater appreciation of the chemical representations as explanatory tools and approximates students' chemistry academic learning profile.

Keywords:
Chemical representations
Representational competence
Chemistry academic profile
Mixed methods
Manila
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Introduction

The spectrum of the different fields of studies have their respective language which serves as the common measures of understanding what the discipline is all about. Being an abstract subject, chemistry is unique because, unlike other disciplines, it is based on one main theory – the particulate nature of matter – that is used to explain and describe processes at the nanolevel of the behaviour of matter.

Chemistry is often regarded as a difficult subject, an observation which sometimes repels learners from continuing with studies in chemistry (Sirhan, 2007). There is some justification for this perception. Chemistry has a specialized vocabulary, mathematical operations as well as representations that are unique to the discipline. The abstract nature of chemistry requires high level of skills to fully comprehend its underlying entities and these skills are often associated to the students' deeper understanding how concepts can be represented or illustrated aside from the results of examinations conducted to measure their chemistry competence.

Explanations of chemical phenomena rely heavily on understanding the behavior of submicroscopic particles and because these particles are invisible, explanatory tools such as chemical representations are central to the learning of chemistry. They are used in explaining scientific and chemical concepts to enhance students' learning and understanding and develop learners' mental models for chemical concepts and the submicroscopic level of chemical representation of matter (Johnson-Laird, 1983). For sufficient understanding of chemistry phenomena, teachers and students must be able to achieve and demonstrate the transfers between the phenomenon, its submicroscopic world and symbolic representations (Johnstone, 1993).

Representations have played an important role in the development of science. Progress has been associated with the creation of new representational forms that allowed scientists to think and communicate differently about scientific phenomena. There is actually an integral relationship between the symbols of chemistry and the understanding that scientific community have of their domain. In the real setting, students' learning and understanding of chemistry is largely dependent not only on the clear explanations of the concepts but more so, with the portrayal of multiple chemical representations.

Sphere of Reference

The Nature of Representations

The term representation may be used with different connotations generating possible misunderstanding or confusion. To Hughes et al., (1995), the definition of the word "representation" means something that represents another. The word represents has numerous meanings including: to symbolize, to call up in the mind by description or portrayal or imagination, to place a likeness of before the mind or senses, to serve or be meant as a likeness of; to describe or to depict as. These terminologies reinforce the descriptive, symbolic and recognizable role of representations in explanations.

On his dissertation, Chittleborough (2004) emphasized the metaphorical nature of representations. A metaphor, in a literal sense, provides a description of phenomena that is real in terms of something with which the learner is more familiar. Under this definition, all representations used in chemistry such as models, analogies, equations, graphs, diagrams, pictures and simulations, can be regarded as metaphors because they are helping to describe an idea – they are not literal interpretations, nor are they the real thing.

Representations serve a special function within the situative theoretical perspective since representations do not have meaning in themselves. Rather, meanings are characterized as relationships between the representations and the objects and events to which the representations refer but that are not present. As such, representations – such as written or drawn symbols, iconic gestures or diagrams, and spoken, gestured, written, or drawn indices – are not intended to be treated as objects themselves but as things that "stand for" or "refer to" other objects, representations, or situations. That is, the meaning of representations does not inhere in the qualities of the representations themselves but are derived as people interpret them, thereby constructing semiotic, "refers to" relations between occurrences of the representation and entities or events that they designate. Creating this refers-to relationships is an important practice of a community and a source of their shared understanding. As people engage in activities in a community, they become "attuned" to the affordances and constraints of the material and symbolic resources of its various settings. Crucial to the function of any social system or community are the conventions of interpreting meanings of representations. From a situative perspective, learning can be viewed largely as a progressive attunement to disciplinary ways of seeing and using representations within a community (Goodwin, 1995).

Levels of Chemical Representations

When describing chemistry phenomena, chemists generally present concepts at three levels of knowledge representation: the macroscopic, submicroscopic, and symbolic levels (Johnstone, 1991).

The macroscopic level, is a concrete level corresponding to observable objects. At this level, students observe the chemical phenomena in their experiments or experiment (Johnstone, 1991; Treagust, Chittleborough, and Mamiala, 2003). These representations are obtained through actual observations of tangible objects or phenomena that can be seen and perceived by the senses or can be a daily experience of learners. The learner could represent the observations or activities in a variety of modes of representation, for example as written reports, discussions, verbal presentations, diagrams and graphs (Farida et al, 2010).

The submicroscopic level, is an abstract level, but corresponding to observable phenomena at the macroscopic level. This level is characterized by concepts, theories, and principles used to explain what is observed at the macroscopic level, using things such as the movement of electrons, molecules, or atoms (Johnstone, 1991). It is closely related to the underlying theoretical model to dynamics explanation of the particulate level. Modes of representation at this level can express start from the simple to use computer technology e.g. using words, two-dimensional, three-dimensional images both still and moving or simulation (Farida et al, 2010).

The symbolic level, is used to represent chemical and macroscopic phenomena by the use of quantitative and qualitative symbolic language such as chemical equations, mathematical equations, diagrams, pictures, graphs, reaction mechanisms, analogies and model kits (Johnstone, 1991)

The three levels of representation of matter provide a framework for understanding the relationship between the various representational forms in which chemistry appears. Just as computers zoom in and out, the depiction of chemicals can change from the reality of the macroscopic level, visible and tangible to the sub-microscopic level that is not visible to the naked eye and is a manifestation of the atomic theory of matter. The understanding of the submicroscopic level is not always clear as it has qualities of reality, representation and theory. These qualities appear incongruous – but are not. Understanding not only the actual content of the sub-microscopic level but also its position and role in providing explanations is what makes the sub-microscopic level so important (Kozma, 2003).

Representational Competence

Representational competence is a term used to illustrate a set of skills and practices that allow a person to reflectively use a multiplicity of representations, singly and together, to think about, communicate, and act on a perceptual physical entities and processes (Kozma, 2000). While those with little representational competence in a domain rely primarily on the surface features of representations to derive meaning (Kozma and Russell, 1997) or on the mechanical application of symbolic rules (Krajick, 1991), those with more skills have come to use variety of formal and informal representations together to explain a phenomenon, support a claim, solve a problem, or make a prediction within a community (Amman and Knorr Cetina, 1990). For chemists, the act of using representations to successfully construct chemical understanding at one constitutes the meaningfulness of the representation and confirms the user's ability to participate in a representational, meaning-making activity (Kozma, 2003). One can neither understand chemistry without using representations nor use representations of the domain without some understanding of chemistry. These skill sets mutually evolve and constitute each other. To characterize this skill set, Kozma (2003) proposed a conceptual structure that organizes representational competence into characteristic patterns of representational use at five stages or level. This structure corresponds to a developmental trajectory that generally moves from the use of surface features to define phenomena, which is characteristic of novices within a domain, to the rhetorical use of representations, which is characteristic of expert behaviour.

Level 1. Representation as depiction. When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.

Level 2. Early symbolic skills. When asked to represent a physical phenomenon, the person generates representation of the phenomenon based on its physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper).

Level 3. Syntactic use of formal representations. When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate.

Level 4. Semantic use of formal representations. When asked to represent a physical phenomenon, the person correctly uses a formal symbol system to represent underlying, unobservable entities and processes. The person is able to use a formal representational system based on syntactic rules and meaning, relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features.

Level 5. Reflective, rhetorical use of representations. When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. Learner can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another.

Conceptual Framework

Learners with little representational competence in a domain depend on the observable entities of representations to show how do they understood the concept (Chi, 1993), while those with more skills have come to use a variety of formal and informal representations together to explain a phenomenon, support a claim, solve a problem, or make a prediction within a community of practice (Amman & Knorr Cetina, 1990).Consequently, representational competence is the complement of chemical understanding, the first focusing on the activity of using representations and the second focusing on the resultant meaning construed from this activity.The features of different representations afford different ways of thinking and talking about the phenomena they represent.

Most students' understanding of chemistry is constrained by the perceptual experiences from their daily lives. They tend to stay at the sensory level and are unable to visualize and interpret molecular and symbolic representations (Ben-Zvi et al., 1986). In addition, although most empirical studies have shown positive results of using representations for chemistry learning at the high school and college levels, the learning dilemmas in terms of how to use them in the classroom context should not be oversimplified. O'Connor (1997) opined that teachers must give much attention to the selection, use, integration and limitations of representations.

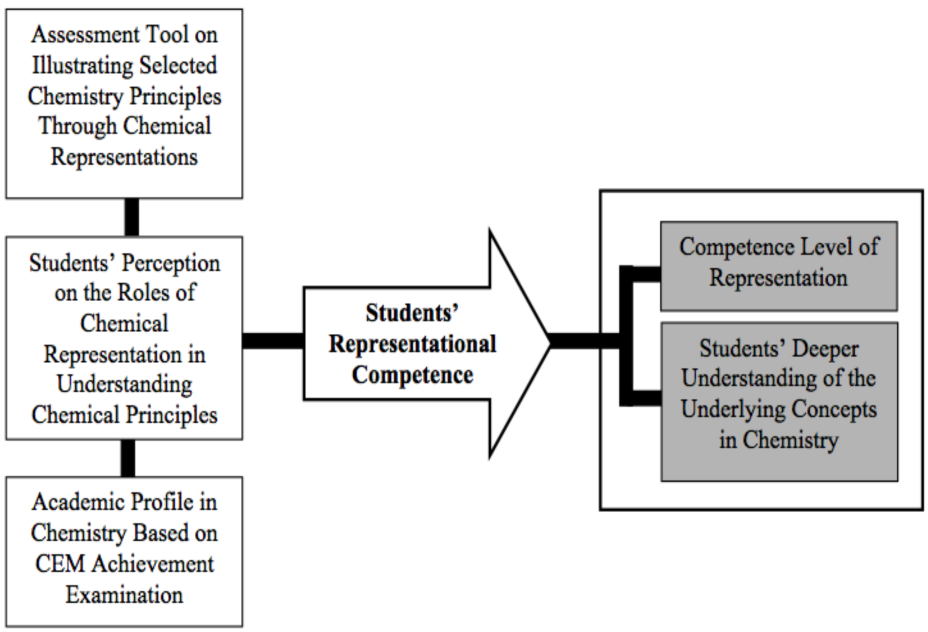

Figure 1. *Research Paradigm*

Figure 1: *Research Paradigm of the Study*

Methodology

The study utilized the qualitative and quantitative research methods. In the qualitative part, the use of task-based instrument with a scoring guide depicts a usual way of assessing students' understanding of particular concepts. These concepts were obtained from the lessons on the following major topics in high school chemistry: classification of matter; chemical bonding; chemical equation; concept of solution; and behaviour of gases. In the quantitative aspects, the utilization of a modified descriptive survey was applied.

Research Setting and Participants

The participants of the study included fifteen (15) senior students which were selected through purposive random sampling from a private school in Metro Manila.

Research Instruments

To determine the students conceptual understanding of chemistry concepts through representation, five (5) tasks were given to the students. Each task corresponds to the selected chemistry principles which are discussed and illustrated through chemistry representations. The tasks allow the students to represent and illustrate on their own the depth of their understanding on the chemistry concepts being implied.

In the assessment of the students' response on the given tasks, a scoring guide patterned from Kozam's (2005) representational competence level was developed and used. The face and content, especially the items included on the evaluation of students' competence level of representation was validated by selected experts on the field through a checklist designed by the researcher. The chosen evaluators were asked to scrutinize in general the face and content validity of the instrument and provided suggestions for further improvement. The evaluators included a high school chemistry teacher, tertiary chemistry educator and a measurement and evaluation expert.

Similar to that of Kozam's (2005), the rubric utilized a five-point scale (1-5) to indicate the hierarchy of students' level of understanding using representations. Meaning, a Level of 1 corresponds to 1 point and so on and so forth. Indicators on each scale were provided as guide for the possible responses of the students.

Initially, common students' misconceptions of chemistry concepts in using representation were determined by reviewing their responses on the tasks given. This included the common correct and incorrect answers in relation to the level of representational competence. The common misrepresentations were identified and the frequency per cluster was determined.

A modified instrument which measures students' perception on the use of chemical representations adapted from the study conducted by Treagust, Chittleborough, and Mamiala (2004) and Grosslight (1991) was used to measure students' personal understanding, perceptions and view of mental models. The instrument is a 32 item pencil and paper questionnaire that requires students to respond to a 4 point Likert-type scale. The thirty-two (32) items in questionnaires are divided into six (6) major aspects namely: (a) chemical representations as multiple representation; (b) chemical representations as exact replicas; (c) chemical representations as explanatory tools; (d) uses of chemical representations; (e) the changing nature of chemical representations; and (f) the personal use of chemical representations.

Data Analysis

In the analysis of the data obtained from the respondents, the descriptive statistics of mean and standard deviation and frequencies were used to describe the general characteristics of the respondents on the variables considered in the study.

In terms of the general competence level of representation of the students, frequencies and percentages were used on each task to compare the most and the least common level of representation acquired by the students. The same treatments were also adapted in comparing the students' level of understanding on each task.

The descriptive statistics of mean and standard deviation were used in the quantitative analysis of the students' responses on the questionnaire. Moreover, the Chi-square test of independence with Yate's correction was employed to verify the significance of the association between the students' academic profile in chemistry and their representational competence levels.

Results and Discussion

Students' Representational Competence Level

The chemistry representational competence level of the students subjected to study was derived using the 5-task instrument where the students were asked to construct their own chemical representations based on how well they understood the concepts given on each task. The table below summarizes the distribution of students per competence level on the content of the task instrument:

Table 1. Summary of students' representational competence level.

Task	*Frequency* Level 1	Level 2	Level 3	Level 4	Level 5
(1) Draw the difference between a concentrated and diluted salty water	2	8	3	2	0
(2) Draw the difference between an element and a compound	6	6	1	2	0
(3) Draw and illustrate the formation of ionic bond between sodium and chlorine	3	10	1	1	0
(4) Draw the chemical reaction between hydrogen gas and oxygen gas	1	4	2	7	1
(5) Draw and illustrate the concept of Charles' Law	3	4	8	0	0
Frequency of Competence Levels	15	32	15	12	1
Percent Distribution	20%	43%	20%	16%	1%

As a sort of summary, majority of the chemical representations of the students are on Level 2, early symbolic symbols, where the use of representation based on physical features supported with symbolic elements is commonly generated. According to Kozma and Russell (2005), under this level, the student may be familiar with a formal representational system, but its use is merely a literal reading of a representation's surface features without regard to syntax and semantics.

The task which rated as the most number of high levels as compared to the rest is the one which deals with chemical equation. While the task which rated as the most number of low levels is about the concept of chemical bonding.

Analogies were commonly used by the students in Level 1. Most of these analogies are based on the personal perception of the students on how the objects or concepts look like. The knowledge on graphical representation was also observed to be extensive among the respondents.

Analysis on Task 1

Table 2. Frequency distribution of students' representational competence level on the first task

Clusters	*Frequency* Level 1	Level 2	Level 3	Level 4	Level 5
I	0	2	2	1	0
II	1	2	1	1	0
III	1	4	0	0	0

Table 2 shows that majority of the responses, about 60%, are concentrated on Level 2, coming mostly from the Cluster III students. This chemical representation is described as early symbolic symbols by Kozma and Russell (2005). On this level, the students are after the physical features of the concepts but also try to include some symbolic elements to accommodate the limitations of the medium. The outcome of the students' chemical representations supports the study conducted by Calik and Ayas (2005) which focuses on eliciting students' conceptions of the types of solutions and from the study of Jansoon (2009) about understanding mental models of dilution where in less able students presented representations and described the events of dilution and concentration at the symbolic level. Only two students coming from Clusters I and II obtained a level 4 by indicating the presence of sodium chloride on the salty water. None of them proceeded deeply on representing the dissociation of salt or the separation of ions in the solvent.

Analysis on Task 2

Table 3. Frequency distribution of students' representational competence level on the second

task

Clusters	Frequency				
	Level 1	Level 2	Level 3	Level 4	Level 5
I	1	1	1	2	0
II	2	3	0	0	0
III	3	2	0	0	0

It can be deduced from Table 3 that the representational competence level of the respondents across the three clusters is rated between Levels 1 and 2. The rating of Level 1 was observed from the common use of chemical symbols of the familiar elements and compounds. The rating of Level 2 introduces another dimension of students' conception of scientific principles in terms of the use of analogy. Forty percent (40%) of the students differentiated element and compound based on their personal depiction through the use of analogies.

The responses of the students on the difference between elements and compounds are related to the study conducted by Stains and Talanquer (2002) where the results indicated that the mental association between the concepts of molecule and compound was stronger in students with higher levels of preparation. Advanced students seemed to differentiate between elements and compounds using an alternative classification system based on molecular structure rather than on chemical composition.

Analysis on Task 3

Table 4. Frequency distribution of students' representational competence level on the third task

Clusters	Frequency				
	Level 1	Level 2	Level 3	Level 4	Level 5
I	0	3	1	1	0
II	0	5	0	0	0
III	3	2	0	0	0

Over all, most of the chemical representations of the students on the third task is given a level of 2. Seventy percent (70%) of the respondents, 10 out of 15, were rated Level 2 on their representational competence level in illustrating the formation of ionic bond between the atoms of sodium and chlorine. These 10 respondents unanimously draw the chemical symbols of the elements sodium and chlorine and placed a line between them to indicate the bond that exist. In addition, together with the rest of the respondents, except for one, the knowledge on the valence electrons as the one responsible for chemical bonding is very visible on the resulting representations of the students. However, only one student has able to place an arrow instead of line, to show the transfer of electrons coming from the sodium atom and going to the chlorine atom, making the representation to be graded as Level 3.

According to Bradley and Brand (1985) a constant interplay between the macroscopic and microscopic abstract levels of thought represents a significant challenge among learners and this has been proven on the study about the students' comprehension of chemical bonding by Taber and Coll (2002). There are many literatures which suggest that students have misconceptions about the concepts associated with chemical bonding such as the attribution of macroscopic properties to particles (Perez et al, 2017). Some of these misconceptions cut across the grade levels as well as across countries, whereas others maybe specific to age groups and cultures. Moreover, more studies have concentrated to secondary level (Unal et al., 2006).

Analysis on Task 4

Table 5. Frequency distribution of students' representational competence level on the fourth task

Clusters	Frequency				
	Level 1	Level 2	Level 3	Level 4	Level 5
I	0	0	1	4	0
II	0	1	1	2	1
III	1	3	0	1	0

Based on the responses given by the students on the fourth task, majority of them are knowledgeable about the important parts of chemical equations. The portion of the reactants, products and arrow are evident on the illustration of the students. Moreover, the inclusion of stoichiometric coefficients has also displayed the complete understanding of the students on what a balanced equation is all about.

Comparing the representational competence level of the three clusters, the higher level is more concentrated on Cluster I, the responses of the second cluster is quite disperse while the competence of the last cluster in making use of representations is much more intense on Level 2.

From the works of the three clusters of students on the fourth task, common alternative conceptions like the misrepresentations of the size of atoms; writing the formula of the diatomic forms of oxygen and hydrogen and the inappropriate use of symbols on the chemical equations like the arrow between the reactants and products were observed.

On the study of Heitzman and Krajcik (2005), they found out that students at all levels of chemistry have difficulty in using chemical representations, such as the inability to translate chemical representations into other forms. They also found that when asked to describe a chemical equation, few students included general concepts about chemical reactions, that their descriptions were direct translations of the process and chemical symbols, and that sometimes these translations identified the symbol rather than the role of the symbol in the chemical equation.

Analysis on Task 5

Table 6. Frequency distribution of students' representational competence level on the fifth task

Clusters	*Frequency* Level 1	Level 2	Level 3	Level 4	Level 5
I	1	0	4	0	0
II	1	1	3	0	0
III	1	3	1	0	0

About 53% of the students under study were rated Level 3, 27% is under Level III and 20% were Level I on their chemical representation of one of the gas laws, the Charles' Law. All of them used graphical representation to show the relationship between the variables volume and temperature. The term "directly proportional" lead the students to construct the graph and relate the two variables.

However, graphs, while symbolic, seem require a more complex type of mental process to understand the principle according to the dissertation by Sande (2010). Aside from the graphical representation, a full understanding of the concept requires critical interpretation of the graph by supplying examples and illustrations. This was made visible to the works of most of the respondents.

Correlations of Representational Competence Level with Academic Profile

The table below shows the summary of the cluster of students' representational competence on each of the level:

Table 7. Summary of students' representational competence level

Task	***f*** **Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Cluster I	2	6	9	8	0
Cluster II	4	12	5	3	1
Cluster III	9	14	1	1	0

Using the data reflected on Table 7, chi square test of independence with Yates' Correction was used to determine the correlation of students' representational competence level with that of their academic achievement in chemistry. It revealed that the computed critical value of 16.07 is greater than the critical value of 15.507 significant at 0.05. This implies that the value is significant, meaning the academic achievement in chemistry and the representational competence of the students are significantly related. It can also be interpreted that the ability of the students on chemical representations has a direct relevance on their academic performance. Further, it may suggest that the knowledge of students on the conceptual aspects of chemistry is really needed on how they present their understanding through chemical representations. This is reflected on the mode of assessment given by the CEM using multiple choice questions which are purely conceptual in nature.

Views on the Role of Chemical Representations

The instrument utilized is divided into six major aspects. The items on chemical representations as multiple representations explore students' acceptance of using a variety of representation simultaneously, and their understanding of the need for this variety. The items on chemical representations as exact replicas refer to students' perceptions of how close a model is to the real thing. The items on chemical representations as explanatory tools refer to what a model does to help the students understand an idea. This scale includes providing visual enhancement, generating a mental model or providing a concrete representation. The items on the uses of chemical representations explore students' understanding of how models can be used in science, beyond their descriptive and explanatory purposes. The items on the changing nature of chemical representations address the permanency of models while the items included on the personal use of the model explores the students' personal encounters in the utilization of multiple representations in learning chemistry.

Table 8 shows the comparison of the mean scores and standard deviations of the different aspects of the instrument:

Table 8. Mean scores and standard deviations of the six (6) aspects on students' views on the role of chemical representations in understanding chemistry

Aspects of Chemical Representations	**X**	**Q**	**SD**
Chemical Representations as Multiple Representations	3.27	A	0.67
Chemical Representations as Exact Replicas	2.86	A	0.77

Chemical Representations as Explanatory Tools	3.48	A	0.70
Uses of Chemical Representations	3.36	A	0.67
Changing Nature of Chemical Representations	3.31	A	0.69
Personal Use of Chemical Representations	3.16	A	0.65

X = *mean*, Q = *qualitative description*, SD = *standard deviation*

The table indicates that the distribution of responses of the students on the different aspects about the use of chemical representations in understanding chemistry principles is concentrated to the agree scale. The aspect on chemical representations as explanatory tools has the most highly agreed items of the students while the aspect on chemical representations as exact replicas has the lowest mean score. The closeness of the standard deviations for each aspect signifies that the students subjected to the study have a common notion of what chemical representations is all about.

Conclusion and Implication to Teaching and Learning

This research provides a framework of finding out the extent on how the students in chemistry understand chemical principles using its language, the chemical representations.

The respondents of the study represents high school learners of chemistry who are unanimously rated as Level 2 or under the symbolic level. The process of students' learning has limitations. In addition, specific period of time and development is needed as learner progresses in their representational competence level. Alternative misrepresentations and conceptions, as result of their learning limitations, provide ample information on areas where learning should be emphasized.

Considering the academic achievement in chemistry of the students based on the standardized examination, it was found out that there is a significant relationship between the students' academic achievement in chemistry with that of their representational competence level.

The students evidently showed a good understanding of what a chemical representation or a mental model is by drawing a negative response that these tools should be an exact replica. Moreover, the students confirmed a greater appreciation that chemical representations are just explanatory tools.

The instruments and rubrics used in this study can be used in other studies to further validate the findings on the level of competence of students in the specified topics.

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