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First Year Undergraduate Students' Difficulties with Ball-and-stick Molecular Models

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Abstract: Previous studies show that students have difficulties in understanding and using molecular visualization tools. This study focuses on the ways in which first year chemistry undergraduates use ball-and-stick molecular models to explain the concept of addition reaction and the difficulties that they face using the models. Video recordings of interviews with undergraduates manipulating ball-and-stick models to solve problems related to reaction mechanisms are analysed to determine if they are able to elucidate their understanding with use of models. The results showed that students have difficulties with viewing the ball-and-stick models from the proper perspective and understanding the relationship between the various structures that they have created using the models. They also find the use of ball-and-stick models tedious and prefer drawing molecular structures on paper to explain their ideas. Implications for the teaching using ball-and-stick molecular models are discussed.

Key words: Representations in chemistry, organic chemistry, learning difficulties in chemistry

I. Introduction

Chemistry is regarded as a difficult subject for students (Johnstone, 1993). To fully understand the reactions that they see, students have to understand the entities involved and processes occurring at the sub-microscopic level as well as communicate their understanding through representational language and notation (Johnstone, 2000). While chemists use language and representations such as structural formulas and ball-and-stick models as cultural tools to conduct inquiry (Nyle, 1993), it has been found that students do not understand the role of representations in chemistry and have difficulty interpreting chemical representations (Kozma & Russell, 1997). They also have difficulties visualizing structures and processes at the sub-microscopic level (Tasker & Dalton, 2006). As a result, students are unable to competently establish conceptual relationships among macroscopic, sub-microscopic and symbolic representations (Kozma, 2000)

Scientific models in the forms of symbolic representations, physical concrete models, computer molecular animations and simulations can help students understand abstract, invisible chemistry processes (Treagust & Harrison, 1999). Significant amount of work has been done in the area of visuospatial thinking in chemistry learning (Bodner & Domin, 2000; Habraken, 1996; Nyle, 1993; Wu & Shah, 2004) which emphasizes the importance of the use of representation by students in creating mental models for understanding chemistry concepts. However, students have difficulty with abstract representation when their thinking depends greatly on more concrete sensory information (Ben-Zvi, Eylon & Silberstein, 1986; Griffiths & Preston, 1992). Even undergraduates have limited understanding of the models used in chemistry (Ingham & Gilbert, 1991) despite modeling being 'a common, intrinsic behavior used in everyday life and also in the chemistry classroom.' (Chittleborough & Treagust, 2007, p. 275).

The objective of this study is to gain insight into how first year chemistry undergraduates use ball-and-stick molecular models to explain reaction mechanisms and the difficulties that they face in using the models. This study therefore situates itself in line of research concerned with molecular modeling in the area of organic chemistry (Head, Bucat, Mocerino, &

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Treagust, 2004; Jones, 2001; Treagust, Chittleborough, & Mamiala, 2004)

II. Literature Review

Representations central to chemistry can pose difficulties for beginning chemistry students (Jones, Jordan & Stillings, 2005) and recognizing the importance of visualization in learning chemistry, studies have been conducted to address issues related to helping students overcome the problem of visualizing three dimensional structures (Copolo & Houndshell, 1995; Grosslight, Unger, Jay, & Smith, 1991; Wu, Krajcik, & Soloway, 2001). As high school and tertiary chemistry curricula use a variety of visual representation to introduce fundamental chemical concepts (Noh & Scharmannn, 1997), it is critical for students to be able to comprehend and mentally manipulate chemical representations in order to acquire advance scientific concepts. For example, in the learning of organic chemistry, the assignment of configuration (R/S) to chiral molecules (a pair of molecules with the same chemical and physical properties, but different spatial orientation) requires students to visualize three-dimensional configurations, and then mentally rotate these configurations to differentiate the R and S configurations. The importance of visuospatial thinking in organic chemistry is evident as chemists visualize synthesis processes through sketches of structures which spatially present the imagery of particles and their geometrical shape in two dimensions and compose a spatial language (Nyle, 1993).

Besides exploring how visuospatial thinking in chemistry learning can be enhanced, research has expanded to encompass perception of students towards chemical representations and how students learn chemistry using chemical representations in order to inform the knowledge and skills required to produce pedagogically effective teaching strategies (Wu & Shah, 2004). Treagust *et al.* (2004) discussed students' perception of scientific models and the development of scientific ideas in the context of organic chemistry adding on evidence to students' simplistic and limited use of models to explain abstract chemical concepts (Coll & Treagust, 2001). However, investigations reported regarding students' learning difficulties with representations (e.g. Zieba, Bucat, Mocerino, & Treagust, 2002; Head *et al.,* 2004) in organic chemistry has been few and the broad topic of organic chemistry is typically omitted in science education research on the grounds that it is reducible to the other topics addressed (Gilbert, Jong, Justi, & Treagust, 2002). Further research is thus necessary to provide insights into how students perceive and ascribe meaning to molecular visualizations in order to help students learn with the various molecular representations specifically used during the teaching and learning of organic chemistry (Jones *et al.,* 2005).

In the teaching and learning of chemistry, molecular representations, which include ball-and-stick models, space-filling models, structural formulae, chemical equations and computer models (Gilbert & Boulter, 2001), are considered to be beneficial in assisting students' understanding of chemical concepts (Tasker and Dalton, 2006). Focusing on organic chemistry, the use of physical models and structural representations are common when reactions need to be explained and described (Zieba, 2004) and the use of concrete molecular models to illustrate phenomena in chemistry teaching has been widespread for a relatively long time (Peterson, 1970). More importantly, a recent study investigating the types of models and the topics in which the various models were incorporated in chemistry or science courses has found ball-and -stick model to be the most prevalently used for teaching about organic compounds (Dori & Barak, 2001).

An obvious advantage of such concrete ball-and -stick models of atoms and molecules are that they are tangible and "real" as they can be touched and manipulated in actual three dimensions by learners. In a review of physical molecular models (Hardwicke, 1995), it has been found that ball-and-stick models are good for teaching because they clearly show multiple bonding and internal structures. Molymod kits are widely used and have colour-coded hard plastic balls of various sizes to represent atoms of different van der Waals radius with spokes of flexible plastic representing different types of bonds. These ball-and-stick models function as caricatures of real molecules and are designed to emphasize salient aspects of the target molecule without providing overwhelming details, for example, the non-rotatable nature of double and triple bonds in contrast to the fully rotatable single bond (Harrison & Treagust, 1996). On the negative side, the double and triple bonds are represented by hard plastic sticks so that the single and multiple bonds each appear to be structurally identical when they are not. The ball-and-stick models also cannot satisfactorily depict a benzene ring. In addition, these physical molecular models are not amenable to computational operations like vibrating the bonds and converting from a sp^3 configuration to an sp^2 configuration.

Despite the disadvantages of using ball and stick models, these models are more conducive to teaching than space filling models due to its qualitative nature (Hardwicke, 1995). Studies have shown that when students appreciate the strengths and limitations of the models in that models emphasize only certain aspects of phenomena, their understanding of chemical concepts in molecular terms is enhanced (Harrison & Treagust, 1996). These physical models function as a tool for construction of knowledge for students with a preference for discrete concrete models as the students try to assimilate and accommodate scientific ideas and terminology (Harrison & Treagust, 1996). A study by Ferk and Vrtacnik (2003) on students' understanding of molecular structure representations provides further evidence that concrete representations are more useful to students than abstract representations and when students have the correct perception of the molecular structure, the models can be more readily used in solving tasks of different complexity involving cyclic structures and stereochemical concepts. In addition, a preliminary study by Khan (2005) focusing on the molecular interactions among compounds with hydroxyl groups shows that by constructing visualizable models, students' understanding of molecules and molecular interactions can be fostered. This paper thus argues that using physical models for science communication plays an important role in the formation of visualisation skills as well as aiding understanding of scientific concepts. Therefore, it is necessary and worthwhile for a deeper understanding of how students manipulate common physical model such as ball-and-stick models in explicating their knowledge about organic chemistry.

Ⅲ. Purpose

This paper focuses on presenting data that answers the following research question: How do undergraduates use ball-and-stick model to explain addition reaction mechanisms and what are the difficulties that the undergraduates face in using the ball-and-stick models?

This work takes into account the social and discursive practices where students are engaged in explaining science by involving students in paired interviews where they have opportunities to coordinate within and across different types of chemical representations in a meaningful way (Wu, 2003). Thus, this paper aims to explore how students use ball-and-stick models to explain chemistry processes under naturalistic condition (non-examination, conversational environment) and to provide a typology of the difficulties that students have with the use of such chemical representations as they attempt to explain reaction mechanisms to the interviewer.

Ⅳ. Methodology

Participants in the research interviews were drawn from a first year undergraduate organic chemistry course from a public university in Singapore. Twenty-two volunteers from an introductory organic chemistry module class were interviewed when they were half-way through their module which had already covered addition reactions in their lectures, tutorials and test. Except for two students who were interviewed individually, the remaining twenty students were interviewed in pairs as they felt more at ease with such a pairing arrangement.

The semi-structured interviews lasted between twenty minutes to forty minutes, and students were requested to manipulate physical models to elicit their understandings of addition reaction. The interviews were videotaped to collect data on how students manipulate the physical models and answer questions posed during the tasks. The task involved giving the students the molecules as shown in the following diagram:

This task was completed by all 22 students and involved the use of ball-and-stick models of 3-methylbut-1-ene and hydrogen chloride. This reaction

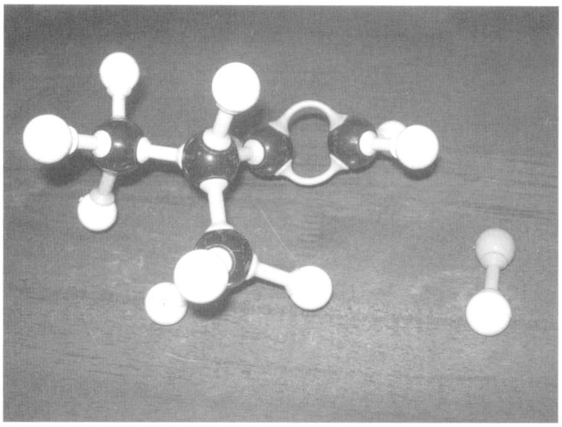

Fig. 1 Ball-and-Stick models given to students for manipulation during interview

was chosen as it is a very common example cited in university organic textbook to illustrate the concept of structural rearrangement (McMurray, 1992) and served a threefold function. Firstly, students who did not know structural rearrangement that often occur during the reaction of hydrogen halides with branched alkenes, most likely could still proceed on with the interview as they probably would still be able to explain the simple addition reaction with the given models. Secondly, if students could not explain the additional reaction process, they might still be able to explain the hydride shift based on the concept of carbocation rearrangement for stability if prompts were given to guide them to the stage of constructing the carbocation. Thirdly, the secondary carbocation that resulted provided opportunity for students to visualise the bulky methyl groups that might hinder addition of the chloro group for which students might suggest as an impetus for hydride shift to occur. In this way, this task offered a myriad of opportunities for students to explore the concept of addition reaction mechanism with consideration of steric and stability factors in the final formation of products. It has to be acknowledged the sp^2 nature of the carbocation formed during the addition reaction cannot be represented by the ball-and-stick model but as the chirality of the products are not emphasised in the interview, this deficiency would have limited effects on the students' explanation of the reactions.

Therefore, given the three-dimensional physical models, students were asked to explain the products that could be formed when the two molecules react. The students were expected to be able to recognise the symbolic aspects of the representation and manipulate the models while explaining the formation of products. The alkene molecule was first given to the students and they were asked questions that help orientate them to the molecule:

1. What type of molecule do you think this is?
2. What is the most interesting feature that you can identify in this molecule?
3. What is the functional group in this molecule?

After which, students were given the molecule of hydrogen chloride and asked:

1. What do you think will happen when the alkene molecule reacts with this HCl?
2. What are the products that can be formed when they react?
3. Is there only one product possible?
4. Can you demonstrate and explain with the models how you arrive at the product that you have constructed?

Data in the form of interview transcripts were transcribed verbatim. The video recordings were analysed using the principles of Interaction Analysis (Jordan & Henderson, 1995). During transcription, the interviews were segmented into categories of self-introduction of participants, free expression about learning difficulties in chemistry, and explanations of students when they were given the three-dimensional models for manipulation. Locating the onset of students' explanation of the addition process, the transcripts were further coded and analysed for speech, gestures and students' manipulation of the models. The codes emerged from collective analysis of this whole set of video recordings by both authors watching the videotapes together, identifying segments of video clips that demonstrated students' difficulties characterized by the participants' superficial or incorrect explanations of concepts as well as participants' explicit expression of having difficulty with a particular aspect of explanation while manipulating the physical models. Field notes collected during interviews were used to map the students' understanding of addition reaction with their ability to handle the interview task which aided in the classifications of students' difficulties with the use of ball-and-stick molecular models.

V. Findings

This section presents analysis of how students used three-dimensional ball-and-stick models to discuss addition reaction. Part I illustrates the types of difficulties students encounter with the use of physical models afforded by the interview session and Part II focuses on how students explain the addition process despite encountering difficulties with the physical ball-and-stick model.

1. Part I: Student difficulties with the use of ball-and-stick model

The table below illustrates the percentage of students who expressed difficulty in the use of ball-and-stick models during the interviews.

With regards to difficulties arising from the use of the ball-and-stick model, the physical model was found to be unable to help students gain a better insight of the molecule in question. Ten students (45%) reported difficulty in viewing the model from the best perspective that would enable them to understand what was being discussed. This difficulty is illustrated by an example of an interview in which student A and student B were engaged in visualising a ball-and-stick model of 3-methylbut-1-ene:

Student A:	I don't like this model as it is very difficult to visualise. I think it is easier on paper. On paper it doesn't look like this (points to the ball and stick model) If you draw a C=C and show it to me, it is better. I will take some time to understand the model.
Interviewer:	Please elaborate.
Student A:	Just focus on C double bond C, just that part now. By looking at the model, how do you know whether it is a double bond or single bond?
Student B:	From the diagram of the molecule printed on paper?
Student A:	No, as in the model. How do you know it is a double bond looking at the model?
Interviewer:	Student B saw the double bonds in the model.
Student B:	There are two bonds here (points at the two grey bonds attached to two black carbon atoms).
Interviewer:	It looked like this right? (Interviewer takes the model from Student B) She spotted this. (Interviewer points to the double bonds)
Student A:	Double bond in paper looks like this (Gestures with hands in the air to show two parallel lines). I know it is alkene not by looking at the double bonds, but because I saw one H here and one H there. (Points to one hydrogen atom of the doubly bonded carbon and then points to the adjacent hydrogen atom attached to the doubly bonded carbon atom) I didn't see the double bond like Student B has done so.

Note: all transcripts were edited to improve their readability.

Given a molecule, Student B could identify a double bond because from where she was sitting, her visual view included a double bond while from Student A's perspective, the two grey bonds overlapped and she did not see the double bonds but instead saw one hydrogen atom each on the two carbon atoms and she interpreted that as a double bond.

Besides having problems with viewing the ball-and-stick model from the best perspective, many students (36%) also faced difficulty in manipulating the ball and stick model as the joints were very stiff and students often had problems in removing the balls from the sticks. For example, in the transcript below, Student C was constantly complaining about difficulty in removing the double bonds as she tried to construct a carbocation.

Table 1

Result of types of difficulty encountered in the use of ball-and-stick model

Difficulty in using the ball-and-stick model	Number of students who expressed the following difficulty (n=22)	Percentage of students who expressed the following difficulty (%)
Viewing the model from the best perspective	10	45
Physical tedium of using models	8	36
Constructing the intermediate	1	5
Making relationship between constructed model and previously constructed model	7	32

Student C: How do I attach this thing to the carbon?
Student D: We need another bond.
Interviewer: Are we short of one stick?
Student C: It is breaking the double bond, this is difficult.
Interviewer: Just pull!
Student C: It's difficult (Interviewer takes molecule away from Student C and helps to pull out the bond connecting two carbon atoms together).

In the course of explaining the addition reaction, there was one student who struggled to build the carbocation intermediate. Student E was hesitant to break the carbon-hydrogen bonds of the model. During the interview, she was observed to be gesturing over the model rather than engaged in the construction of the intermediate.

Interviewer: I see that you are pointing to the model.
Student E: I am thinking of whether I can shift things around to get a tertiary compound.
Interviewer: Do you think you can shift any bonds?
Student E: I am taking a very long time. Wait. (Points at a carbon atom)
Interviewer: What do you mean when you point to that carbon?
Student E: I am thinking. Is this a primary or secondary carbon? This one is a tertiary carbon. So it must this one for some sort of shift. To shift, my brain stops here. But I know there is a shift (in order for the second product to be formed).

Lastly, making a relationship between constructed model and previously constructed model was problematic for 32% of the students. The process of bond breaking and forming requires movement of electrons which is embodied in the manipulation of the physical models. The construction of a new model (carbocation) entails the 'disappearance' of the previous model (reactant). Students expressed confusion with the use of models to explain the addition mechanism as the model of the reactant useful for referencing does not exist after constructing the carbocation.

Student G: Ball-and-stick models are useful for showing chair conformations and ring flip. But for addition reactions, I can't remember how the model (of the starting material) looks like.
Student F: On paper is better, we can draw the reactants and products.
Student G: Generally better.
Student F: You can see a link when you draw arrows to show the movement of electrons from one molecule to another on paper. But with these models, plucking out a bond means the original model is changed.
Student G: It gets confusing already
Student F: You will not remember where or which electron goes using these models, but on paper, it is very systematic and you can see the whole picture.

These examples above illustrate the difficulties tha students encounter when using physical models. The next section illustrates how students went abou explaining the addition reaction process despite the limitations imposed by the ball-and-stick models as shown above.

2. Part II: Students' explanations of addition reaction mechanism

Students had difficulty labelling the concrete models as they were still not conversant with the IUPAC naming system for organic molecules. As the chemical names of the physical models were not revealed to students, they were observed to be actively involved in naming and labelling the ball-and-stick models given to them in order to provide the missing piece of information. This categorizing was done with the active manipulation of the models as the students were observed to hold up the models and rotate it around with their hands as they examine the features of the models. For example, in the following extract from Student L, as he tried to label the models, he gestured above the models and used it as a resource to organize the alignment of his talk and the visual representation (Goodwin, 1994).

Student L: This is carbon (points at the black coloured balls) this is H (points at the white coloured balls). You have to use the rules to identify the molecule. The first substituent is, hmm, (left hand holds onto to the 3-methylbut-1-ene model, right hands grasps at segments of models intermittently). Ok, this is 1, 2 (points at the doubly bonded carbons). So what is this?

2 carbon cyclo···. Hey, this cannot be cyclo, this is a double bond, so this is an ethane (sic), so you have 1, 2, 3, 4, (finger points at the carbons of the skeleton chain in succession), this is a 4 carbon molecule. So we start off with the ethene, 1, 2, 3, 4, and the third carbon is attached to the methyl (points at the methyl group protruding towards him), so we call this 3 methyl butene, not sure if we should indicate 1 for the double bond, so we shall call this 3 methyl 1 butene.

Typically after the students have successfully labelled and identified the features of the ball-and-stick models, they would proceed to illustrate how the double bond of the alkene model might react with the hydrogen chloride. For a typical electrophilic addition reaction to occur, the pi electrons are nucleophilic sites that react with electrophiles. Thus, the addition of hydrogen chloride should proceed by the pi electrons attacking the electrophile. Two electrons from the pi bond form a new sigma bond between the entering hydrogen and the alkene carbon resulting in a carbocation intermediate that can accept an electron pair from anionic substances to yield a neutral addition product (McMurry, 1992).

Students were aware of the breaking of pi bonds, but none of the students were able to accurately comment that pi bonds of alkene would react with the electrophiles with some students even erroneously linking the term electrophile to mean electron rich species as shown by Student A in example below. Most of the students were vague in their gestures to indicate direction of attack by reactants and were mostly concerned with the physical manipulation of models to illustrate the breakage of pi bonds. However, before the breakage of physical bonds, students tended to gesture the attack with their fingers. This deictic gesture was accompanied by their speech and played an important role in establishing the abstract spaces shared with the participants of the interview (Ochs, Gonzales, & Jacoby, 1996). By grounding the pointing in the context of an impending attack of the pi electrons on the electrophile, the direction of attack was made salient by the gestures of the students, for which an example is illustrated below:

Student A: This is an alkene (looks at interviewer and points at double bond of model). There is a double bond.

Student B: (attempts to break double bond)

Student A: (raises HCl model and points at the hydrogen atom of the model). This is H and this is Cl. Two electrons from this bond (points at bond connecting the H and Cl) will go to Cl (points from the bond to the Cl atom in a curved manner) and this will become Cl minus (points at the Cl atom). So the alkene is electrophilic, it loves electron (sic.), so the electrons will attack the positive part of this H (finger points from the double bond to the HCl's bond and back to the double bond repeatedly in a curved manner). Note that now that the double bond is broken (Student B finally managed to break the pi bond), alright (pauses to break the HCl bond).

Student B: It goes in (attempts to remove the hydrogen atom from Student A's hand).

Student A: Talk about the carbocation (Passes the hydrogen atom to Student B to attach to the alkene model).

Despite having difficulties with the physical models as shown in the excerpts, students as exemplified from the transcription above were able to work collaboratively to break the bonds of hydrogen chloride model and double bond of the alkene to construct a new model. Despite the students' inexperience with the use of models as noted in the field notes, they were mostly at ease with the manipulation of models which correlates with the findings on chemists who were able to coordinate spontaneously generated representations to understand the structures and processes that underlie them (Kozma, Chin, Russell, & Marz, 2000). An example is as shown:

Student S: This molecule (points at alkene model) is···. pentyl (sic). (looks at Student T)

Student T: (stares at the model and nods her head) pentene (sic)

Student S: There is a double bond, so with hydrogen chloride, addition reaction (looks at Student T for affirmation).

Interviewer: Can you please explain the process?

Student T: (takes the double bond and breaks one of the bonds)

Student S: (breaks the hydrogen chloride bond and attaches the hydrogen to the alkene model, creating a model of a carbocation). This one should be a plus (points at the carbon that has only three bonds attached to it) and this chloride will come over to this side (attaches chloride to the carbocation).

Student S and student T have apparently ignored explaining for the first step of the addition reaction mechanism where the nucleophilic pi electrons attack the electrophile of hydrogen chloride to produce a new carbon-hydrogen bond and a carbocation (Meislick, Nechamkin, & Sharefkin, 2000) as shown below:

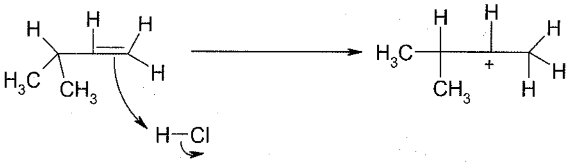

Fig. 2 *Pictorial representation of the first step of addition reaction*

However, they were still able to work together to produce the correct carbocation representation through their interaction. This finding is congruent with report that ball-and-stick models support collaborative work (Chang, Scott, Quitana, & Kracjik, 2004). From the video analysis of the students working in pairs to explain the addition reaction process, the interaction between students involved not just the use of speech, but simultaneously, students were observed to be gesturing and actively manipulating the physical models to express themselves. This activity seems to convey the idea that scientific concepts are simultaneously verbal, visual and action (Lemke, 1998) and viewing interview data from the perspective of giving emphasis on the various modes of chemical representation employed by students can help provide new insights on the types of difficulties students have with chemical representations.

VI. Discussion

This paper provides a typology of the types of difficulties that students face when representing their knowledge using ball-and-stick models. Firstly, students have difficulty viewing the ball-and-stick models from the best perspective, which may hinder their understanding of fundamental chemical concepts that are embedded within the physical models chosen to model at the molecular level. Students' comments during the interviews bring to light that when a teacher holds up a model in class to highlight an aspect, whether it is to show a particular functional group or the spatial arrangement of the atoms, students who are viewing the model from different angles, see the model quite differently from what their teacher expects them to see. This is an important finding as we therefore need to find ways in which to ensure students 'see' what their teachers 'see'. It is only when the same perspective is shared that the concepts can be better explained leading to greater understanding of concepts taught. Thus, teachers need to be careful about which feature of the physical model they are presenting to their students as models sometimes may be too small for students to visualise clearly or certain aspect of the models may be obscured from view of the students depending on their classroom sitting position. Differences between teacher and students' perspective of the physical model due to teachers' lack of topic specific pedagogical knowledge for teaching with physical models (Harrison, 2001) and frustrations of students who are unable to share the same perspective of the physical model as their teacher may result in miscommunication during lectures. In addition, we suggest placing a physical model on a visualizer to project a particular image on a large screen for the students' viewing might be helpful during the explanation process as both teacher and students view the model from an identical perspective as they see the same facet of the model being projected on screen which enables better communication of chemical knowledge (Zare, 2002).

Ball-and-stick models have been acknowledged as a limited tool to model chemical processes (Chang *et al.*, 2004). Although students may still create molecular models, manipulating them to illustrate chemical processes, the physical tedium of rearranging the atoms might be a distraction to the modelling process which perhaps prevents students from learning the intended characteristics of the physical model. In addition, the low permanence of ball-and-stick models that occurs as students manipulate the models during the explanations is problematic as students are unable to relate their explanations of chemical processes with the static view that ball-and-stick models provide. Lastly, despite having the notion of carbocation formation evident from Student E's comment about shifting of bonds, this lone student was unable to bring herself to break the double bonds and construct a carbocation. Previous research suggests that students do not easily understand phenomena from a particle perspective, although such a perspective has many concrete aspects that ought to assist learners of chemistry (Han & Roth, 2005). In the case of Student E, she was unable to utilise the concrete aspect of the ball-and-stick model in terms of the breakability of the bonds to construct the carbocation phenomena that she was thinking about as indicated by her utterance. The rest of the students were able to construct the intermediates and attach values, such as positive signs, to the intermediate carbon, and were comfortable to imagine the non-visible attributes of the intermediate alongside their physical model as the physical models cannot satisfactorily depict a carbocation. Therefore, students need to overcome barriers that may hinder them in the use of different representations for different situations to understand and explain chemistry and this may require students to possess far more than skills required for visualisation of molecular models (Jones *et al.,* 2005).

In addition, when the undergraduates used ball-and-stick model to construct the carbocation, none of them articulated that the constructed model of carbocation was not a good representation of the trigonal planar carbocation. As a result, none of the students were able to suggest an explanation of a top or bottom attack of the carbocation by the bromide nucleophile which could lead to the formation of chiral products. This finding suggests that the ball-and-stick model has limitations in the use for learning of reaction mechanism where the construction of intermediates might be problematic due to the physical attributes of model. It is therefore important for students to understand that the usefulness of models is often constrained by the 'rules' associated with the particular modelling conventions (Zieba *et al.,* 2002) for which teachers may need to highlight when these models are used in the classrooms.

From the interview results, students were generally able to form the products of the reactions with their models and the process requires co-ordination between speech and actions. A study on the modelling approach to science teaching in the classroom (Máquez, Izquierdo, & Espinet, 2006) has highlighted the role of speech, gesture and visual language in the modelling of the water cycle in secondary school. The findings of this work also details in brief how students use physical, verbal and gestural mode of chemical representation to explain the addition reaction mechanism. Thus, an area where important research can be done could be studies of how scientific models presented in the various mode of representation such as visual, graphic, symbolic, verbal, and gesture are understood by students in terms of the aspects of phenomena represented.

VII. Conclusion

This paper describes the difficulties that students face as they attempt to explain the mechanisms of chemical reactions using physical models. Students are unable to view the physical model from the best perspective, construct intermediates and find it tedious to manipulate the ball-and-stick models. The selection of the relevant representations and the provision of an appropriate explanation are central to the maintenance of active involvement of students in the learning of science (Gilbert, Boutler, & Rutherford, 2000). Efforts to overcome students' difficulties with chemical representations thus need to be situated in explanatory contexts where students are involved in the use and manipulation of chemical representations.

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