Chapter 5
Multimodality in Problem Solving

Shien Chue and Kim Chwee Daniel Tan

5.1 Introduction

Problem solving in chemistry education has constantly intrigued researchers (Bennett 2008; Bowen and Bodner 1991; Chandrasegaran et al. 2009; Gabel and Bunce 1994; Krajcik 1991; Tsaparlis and Angelopoulos 2000). In the past, problem solving in chemistry focused on how students might follow the procedural steps of understanding the problem, devising a plan, carrying out the plan, and reflecting upon the actions taken (Bodner and Pardue 1995). While such research had resulted in new knowledge of how students solve problems through a more cyclical approach with the use of symbols and diagrams for visual representation of the problem (Lee and Fensham 1996), a deeper examination of the interactions between the problem solvers and the given task is required (Bodner and Herron 2002). Research on problem solving in organic chemistry mostly focuses on students' cognitive processes during problem solving (Bhattacharyya 2004; Stieff 2007; Tsaparlis and Angelopoulos 2000; Zoller and Pushkin 2007). Often, research reiterate claims that students solve chemistry problems using algorithmic methods and lack understanding of chemical concepts on which the problems were based (Gabel et al. 2006).

Research is beginning to suggest that the use of multiple representations play an important role in helping students construct and communicate chemistry knowledge

S. Chue (✉)
Centre for Research in Pedagogy and Practice, National Insitute of Education,
Nanyang Technological University, Singapore
e-mail: ruikyi@yahoo.com

K.C.D. Tan
Natural Sciences and Science Education, National Institute of Education,
Nanyang Technological University, Singapore
e-mail: daniel.tan@nie.edu.sg

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(Hand and Choi 2010; Nakhleh and Postek 2008; Yore and Treagust 2006). Recent studies on students' learning of organic chemistry (Anderson and Bodner 2008; Bhattacharyya and Bodner 2005) highlight differences in how teachers and students use chemical symbols and structures for communicating chemistry knowledge. It appears that students have difficulty in representing chemical phenomenon using chemical symbols as well as in developing explanations of chemistry reaction mechanisms.

However, there has been less focus on students' use of multiple modal representations as they engage with problem-solving tasks in the context of organic chemistry. While researchers highlight the importance of mental models in the development of problem-solving capabilities (Bodner and Domin 2000; McLoughlin and Taji 2005), much remains to be elaborated about how students can engage in successful problem solving through creation of appropriate representations. Similarly, while graduate students use different representational forms such as verbal and pictorial representations as a common language for communicating scientific information to others (Bowen 1990), little is known if science undergraduates do the same (Bodner and Weaver 2008).

5.2 Multimodality

A multimodal social semiotics epistemology (Kress 2003; Kress et al. 2001) offers a useful way to examine organic chemistry problem solving. The basic concept of multimodality positions knowledge as coconstructed through the coordination of meaning-making resources that is not limited to only language. Language is the primary medium for reasoning and conceptualization in science as well as reporting and persuading others about these claims (Lemke 1998). Without language in the forms of oral, visual, and print, social practices of engagement in knowledge construction are not possible (Norris and Phillips 2003), and this is supported by a study of the coauthorship process in research laboratories where the quality of writing and science produced by novice scientists improved after reiterative process of writing and reviewing with other members of the scientific community (Florence and Yore 2004). Extending beyond speech or writing, semiotic resources such as visuals and even actions are capable of carrying information that contributes to the overall meaning that one intends to communicate. By attending to all modes of communication as part of meaning making, the monolithic emphasis on language as the valued mode of communication in education is superseded by a growing recognition of the multiple modes in which ideas could be represented (Bezemer and Kress 2008; Knain 2006; Kress et al. 2000, 2001).

In science education, a myriad of representations and artifacts are required to represent scientific concepts in addition to speech or writing. These multiple modes of representations are material expressions of abstract scientific phenomenon being experienced and can be understood as individuals' articulations of their observations and knowledge about phenomena (Lemke 2001). For example, it was found that teachers seek to shape students' understanding of the particulate nature of matter through the use of actions, speech, and diagrams (Kress et al. 2001) to provide students with the visualization of abstract notions of particulate interactions. Likewise, undergraduate physics students were found to rely on the affordances of different semiotic resources in representing abstract knowledge for learning (Airey and Linder 2009). For instance, to understand energy transfer, students need to be fluent with definitions of the various types of energy and use and apply mathematical equations as well as graphical representations for quantifications of energy. They also need to engage in physics experiments to experience the abstract concepts in the real-world context. Similarly, learning chemistry requires students to describe chemical reactions textually, graphically, or even with a combination of both in order to translate between multiple dimensional molecular representations of chemical structures (Dori and Barak 2001).

Therefore, ideas about multimodality can be useful in describing and examining problem solving in a semantically rich field such as organic synthesis. This is accomplished by first positioning visual inscriptions, gestures, and speech as common semiotic resources and layering a dynamic view on how the resources are employed for meaning making. While research has established the social and cognitive affordances of multiple representations (Kozma 2003; Schank and Kozma 2002), little research actually foregrounds students as members of the scientific community engaged with multiple representations for problem solving in chemistry. Hence, the purpose of this study is to shed light on how students express themselves within the problem-solving context through the coordination of multiple semiotic resources that reveals scientific knowledge through time.

5.3 The Study

In this study, we examine a pair of students engaged in constructing an appropriate synthetic pathway from initial reagents to the formation of final chemical product in a typical closed problem. Problems of this kind have been suggested to be simplistic as solutions can be reduced to routines or algorithms for which students can be trained to recall and utilize (Wood 2006). However, the choice of a closed problem for this study is deliberate in order to investigate the phenomenon of students' knowledge as multimodal, supported by an analytic focus on language in conjunction with action in forms of gestures and with the students' inscriptions. In this regard, the multimodal approach taken in this paper challenges the notion that students' science knowledge consists of propositions composed of well-defined concepts (Klein 2006) to reveal knowledge as an accomplishment of practical action (Garfinkel 1967) in the context of solving chemistry problems.

By looking at the types of semiotic resource employed for interaction and the functional role they play in students' problem-solving discourse, we aim to uncover and study the social creation and maintenance of scientific knowledge between students. The significance of such an approach is at least twofold: First, a multimodal approach can advance our knowledge about problem solving as more than consisting of cognitive strategies to encompass the use of meaning-making resources within the context and organization of participants' knowledge. It is vital that chemistry teachers recognize and value the constructive, persuasive, and reporting functions that language and other semiotic resources afford during scientific communication. In this way, teachers can examine and improve their own instructional practices on problem solving in order to model effective strategies for their own students. Second, a multimodal approach requires science educators to examine problem solving as a moment-by-moment unfolding event. This is important as close examination of students' engagement in problem solving allows the subtle nuances in speech and nonverbal behavior through which knowledge of science is represented, communicated, and developed to be studied. Hence, our understanding of the act of problem solving expands from knowing the cognitive strategies students employ to include how solutions to given problems are constructed, argued, and communicated through the dynamic interplay of speech, inscriptions, and gestures employed during the problem-solving process.

5.4 Methodology

Two female students, Sally and Heidi, volunteered for this study. They were first year Bachelor of Science (Education) undergraduates enrolled in a compulsory module on introductory organic chemistry. During the problem-solving session, the students were provided with an organic chemistry question (see below) printed on paper with blank spaces for their writings in addition to boxes of Molymod® models.

Using cyclohexene and bromine in carbon tetrachloride as starting materials, explain the synthesis of trans-1,2-dibromocyclohexane.

Problem solving can be defined as "figuring out what to do when one does not already know what to do" (Bowen and Bodner 1991, p. 143). While organic chemistry tutorial questions may look like mere exercises for chemists with wealth of chemical knowledge, the lack of familiarity with such problems for first year undergraduate chemistry students (Bodner and Domin 2000) makes this question about the synthesis of trans-1,2-dibromocyclohexane a challenging problem for them, not simply a recall exercise. The identities of the starting reagents were provided in the question so as to facilitate discussion about how the reagents may react. To solve the given organic chemistry problem, students needed to work out the solution in the following manner though not necessary in the linear order as presented in Fig. 5.1.

1. Draw the structures of cyclohexene and bromine.
2. Draw an arrow from double bond of cyclohexene to delta plus bromine.
3. Draw an arrow from the bond between the two bromine groups directed at the delta minus bromine.
4. Draw a bromonium intermediate with a positive charge.

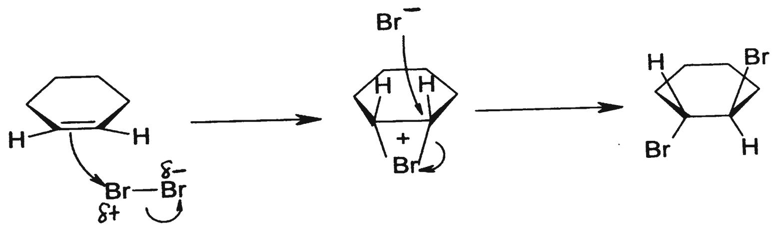


Fig. 5.1 Written solution to given interview question

5. Draw arrow to represent movement of bromide ion to either carbon involved in the bromonium intermediate.
6. Draw the configuration of the final product of trans-1,2-dibromocyclohexane.

The students were informed by the researchers that they could choose to answer the question in any form that they were comfortable with, even if that meant just talking about the question and not writing down anything on the given answer sheet. Students' engagements during the problem-solving session were video-recorded. Subsequently, the video recording was analyzed using Jordan and Henderson's (1995) interaction analysis approach where we ground our assertions in empirical evidence, building generalizations from records of naturally occurring activities and drawing upon our experience and expertise as chemists and chemical educators. The analysis begins with a description of the nature of the interactions obtained from repeated viewing of the two students solving the given organic chemistry problem. This description is followed by discussion focusing on how semiotic resources had been used by students to generate, organize, and communicate abstract scientific ideas during the problem-solving session. This is an iterative process where researchers would make assertions about the semiotic resources observed and the segment of video data was reviewed to check the degree to both researchers would agree to which assertion fits. When an assertion was agreed by all, more segments of video data were viewed in order to gather empirical evidence to support the claims. In cases where assertions were not agreed by all, assertions were reformulated and retested until a consensus that fitted the entire data was reached. To focus our attention on the repeated viewing of video data, we asked questions which were adapted from the work of Jordan and Henderson (1995) such as: What is the trajectory of the inscription/gesture/action? How did it get into and out of the scene? Who are the active agents employing the semiotic resource? How do they function in structuring interaction?

This resulted in labor-intensive work as close transcription of short strips of video recordings was created and individual lines of verbal transcripts were described with regard to duration, function of speech, action of participants, visual representation such as use of inscriptions or physical models, as well as the researchers' interpretations. The microanalysis of video segments, thus, afforded the means to describe dynamic activity involving the use of multiple meaning-making resources.

5.5 Findings

Sally and Heidi began by working out the structure of the final chemical compound and their process of problem solving revolved around the construction of isolated chemical structures. It is interesting to note that while their final written solution as shown in Fig. 5.2 seemed to indicate knowledge about the process of synthesis, their conversation revealed many areas of uncertainty.

5.5.1 Final Chemical Structure

Both students relied on gestures and speech to debate over which type of chemical structural representation to inscribe (Fig. 5.3). With her right-hand pointing finger raised, Sally produced an iconic gesture by tracing the outline of a six-membered carbon ring (Panel 1) as she offered verbal information about drawing a carbon structure (01).

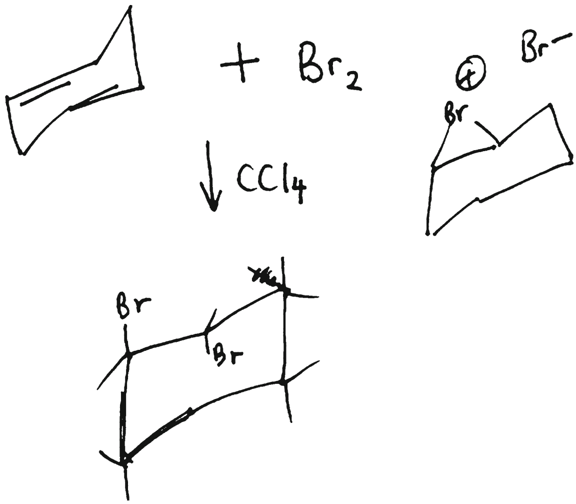


Fig. 5.2 Final written solution of Sally and Heidi

Fig. 5.3 Gesturing structures of final reagents

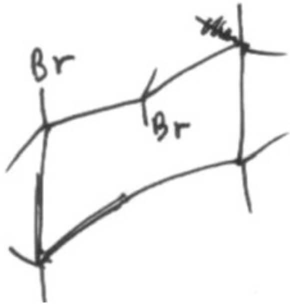
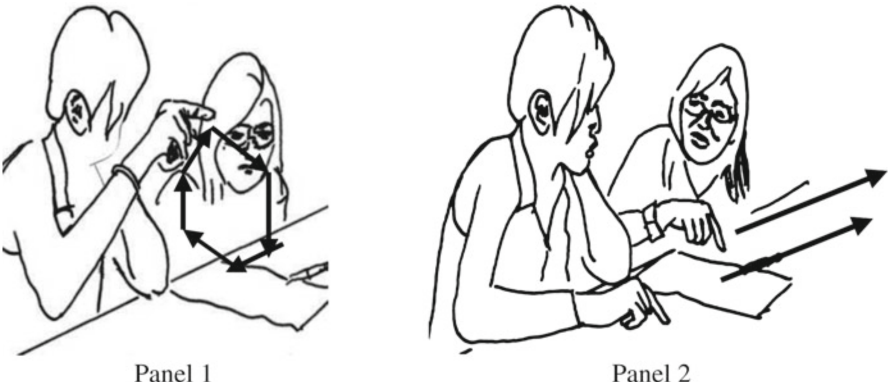


Fig. 5.4 Working out the spatial arrangement of substituent groups

This gesture carried crucial information for Heidi who immediately offered an alternative structure by tracing in quick downward diagonal strokes on the table. While Heidi did not express verbally the chair conformer that she had in mind (02), her gestures illustrated clearly for Sally the chair conformer as an alternative to the cyclic skeletal representation. Although Sally expressed her uncertainty about Heidi's suggestion (03), she proceeded to draw the chair conformer of the final product (Fig. 5.3) which signaled the genesis of knowledge construction on paper.



01 Sally: Draw [carbon].
(*gestures in the direction of arrow, iconically sketching out a skeletal structure*)$_{Panel\ 1}$
02 Heidi: [Draw that].
(*gestures in direction of arrows, iconically representing part of the chair structure*)$_{Panel\ 2}$
03 Sally: Hmm, let's just try.
(*draws chair structure as shown below*)

After the inscription of carbon-hydrogen bonds in the chair conformer, Sally hesitated over the placement of the bromo groups and both students communicated with gestures again to determine the orientation of the two bromine substituent groups (Fig. 5.4). Heidi first asked Sally what "trans" might mean (04). Sally responded silently with a gesture where two pointing fingers were oriented perpendicularly to each other (Panel 3). Both bromo groups can be either in the equatorial positions or the axial positions in the chair conformation of the final trans compound. However, Sally's gesture seemed to indicate an orientation where the substituent groups are 90° away from each other. Her gestures were followed up subsequently with a tentative verbal request for Heidi's affirmation (06). While Sally positioned her pen over the chair conformation of the final structure, Heidi reasoned verbally that if one bromo group was drawn pointing upward, the other should be pointing downward (07). Observing the directions of her pointing figures (Panel 4), the angle between the instance of pointing upward and downward embodied Heidi's conception of the manner in which bromine groups are attached to the cyclic ring. This gesture was similar to Sally's except that the angle between the upward and downward pointing finger was greater. This information was repeated as Heidi this time flipped her right hand in an up-down manner (Panel 5) to demonstrate that her verbal utterance of "opposite side" (08) entailed a direct up-down orientation as materially carried in her gesture. Sally took up Heidi's suggestion and drew the bromo groups in the axial positions (Fig. 5.4).

Panel 3 Panel 4

04 Heidi: Trans 1 2 dibromo, trans is?
05 Sally: […]
(*gestures up and down in opposite direction indicated by arrow1 and 2*)$_{\text{Panel 3}}$
06 Sally: Should be. Is that right?
07 Heidi: Trans [should be one up and down].
(*gestures in the direction of arrow 3 and arrow 4*)$_{\text{Panel 4}}$
08 Heidi: Trans. They are in [opposite side]$_{\text{Panel 5}}$. If you put one up the other will be down.

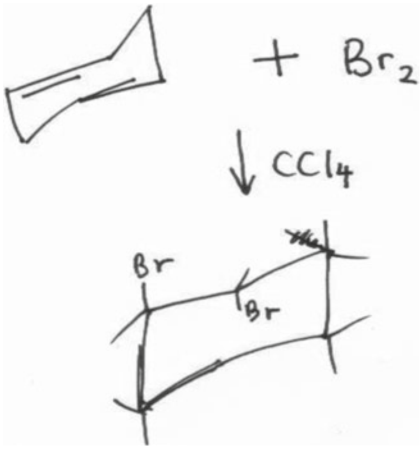
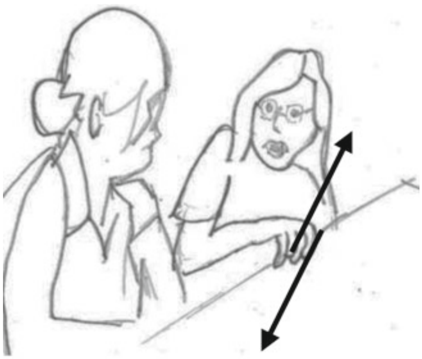


Fig. 5.5 Gesturing to determine structure of initial reactant



Panel 5

(*right hand raised, flipping upward and downward in quick succession*)$_{Panel\ 5}$
(*Sally draws position of two bromine groups as shown below*)

5.5.2 Initial Chemical Structures

After the final chemical product was inscribed, Sally began another phase of problem solving as she prepared to construct the initial reagents. First, she signaled her thoughts about the location of a double bond in the reactant by tracing two parallel lines along the inscribed final compound (Panel 6). Verbally, Sally also informed Heidi that they had to place a double bond at the location where she had previously gestured over (09) and proceeded to draw a cyclohexene at the upper section of the page (Fig. 5.5). Sally subsequently completed the equation with further inscriptions of the chemical formula of Br_2, CCl_4, and the reaction arrow pointing downward to the product.

Panel 6

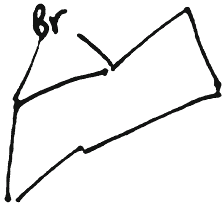
09 Sally: Ok, so we have to put a [double bond here].
(*gestures in direction of arrows twice as shown above over the structure of final product*)
10 Sally: And [reaction with bromine].
(*draws starting compound and writes* Br_2 *and arrow pointing downward with* CCl_4 *inscribed on right side of arrow*)

5.5.3 Intermediate Structure

The pair of students next engaged in drawing "something else" (11). Heidi began by first suggesting to Sally that their written solution required another chemical structure (11). With her fingers held in an inverted cup shape directed at the answer sheet (Panel 7), the metaphoric gesture encapsulated the hazy notion of the intermediate in which speech was equally vague with an ambiguous reference of "something else." Sally interjected to offer new information that the intermediate had a "wing" (12) in rapid speech and repeatedly traced a triangular outline on paper (Panel 8).

After each student had contributed her own ideas about the intermediate, Heidi signaled her readiness to construct the chemical structure on paper by suggesting "let's try" verbally (13). Voicing her thoughts (14), Sally simultaneously outlined the three-membered ring with a clenched fist over the inscription of the starting chemical reagent before drawing the intermediate structure in Fig. 5.6.

Fig. 5.6 Verbal-gestural exchange leading to inscription of intermediate



Panel 7 Panel 8

11 Heidi: I think we need to draw something else right?
(*cupped left hand directed downward at table*)$_{Panel\ 7}$
12 Sally: Something that has a wing…
(*traces shape of triangle with finger*)
13 Heidi: Let's try.
14 Sally: I remember there is a [three member ring].
(*traces shape of triangle with clenched fist over previously drawn starting reagent*) $_{Panel\ 8}$
15 Heidi: I think that's right. Correct, correct.
(*Sally proceeds to draw the bromonium ion intermediate*)

Evaluating the completed structure of the intermediate, Heidi suggested, through an interrogative request, a positively charged bromonium intermediate (16). Heidi's evaluation of the incomplete intermediate chemical structure led Sally to draw a positive charge and a bromide anion in the diagram (Fig. 5.7). Through inscriptional means, Sally acknowledged the information provided by Heidi and at the same time contributed her share of knowledge with an inscription of the bromide ion.

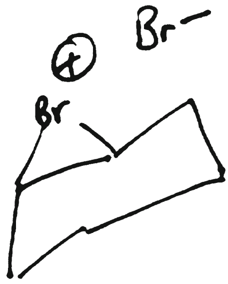


Fig. 5.7 Inscription of intermediate of reaction

16 Heidi: Br, is it positive?
17 Sally: Let's try.
(*adds in positive sign for carbocation and draws a bromide ion*)
18 Sally: Something like that.

5.6 Discussion

Analysis of this single case study leads to two points of discussion. First, we claim that this chemistry problem-solving event involving the two students serves as an exemplar to highlight problem solving as a practical activity of human interaction which goes beyond the confines of cognitive processes to encompass a strategic use of meaning-making resources to construct knowledge as well as report the knowledge to others and persuade others of their validity. By providing detailed description about the events leading to the final solution and the specific ways in which they were constructed through speech, visual inscriptions, and gestures, we show how students collaborate using a myriad of meaning-making resources to construct a reasonable solution. While a conceptual base of content knowledge (Krange and Ludvigsen 2008), mathematical knowledge (Chandrasegaran et al. 2009), and procedural knowledge is necessary for problem solving, it does not preclude the use of meaning-making resources for building new knowledge contingent upon previously constructed knowledge along the pathway of problem solving as exemplified in this case study. Second, we provide a method for investigating problem solving from a multimodal perspective that goes beyond the typical focus on cognitive processes of students during problem solving. Through interaction analysis, which provides a fine comb to untangle the intricacies of student interactions as a multimodal event, data can be examined repeatedly by focusing on the ways students interact and the role of meaning-making resources in the accomplishment of the activity.

In this case example, the students were uncertain of the process of addition reaction mechanism. First, they focused upon the final product and worked backward to derive the structure of the starting compound which indicated their lack of knowledge about how to solve the problem beginning from the starting reagents. Second, in the inscription of the final product, students were unaware of the placement of the two bromine groups in the equatorial position to prevent 1,3-diaxial interactions. Third, the students' focus on the inscription of the intermediate to mediate between the starting and final chemical structures can be understood as filling in a gap in order to fulfill the requirements of the given problem. The lack of inscriptions of arrows symbolizing the movement of electrons as well as the absence of verbal or gestural reference to electron movement indicate that the students may not be aware of the electron movements in the addition reaction process.

Despite their lack of understanding of the addition reaction mechanism, they were able to collaboratively generate a final solution on paper. In fact, the coordination of semiotic resources was critical in enabling both students to solve the given problem. First, gestures enabled students to agree upon an outline for the structure of the final product, 1,2-dibromocyclohexane (01–03). Next, transformation of gestural information occurred as the chair conformer of the final trans product was revealed through visual inscription on paper (04–08). This inscription provided the platform for Sally to gesture over it the location of the double bond of the starting chemical compound, cyclohexene (09). Subsequently, the gestural information was marked down on paper through Sally's drawing of cyclohexene (09–10).

Students had also relied upon gestures to communicate their ideas about the intermediary product formed during the reaction, the bromonium ion intermediate (11–14). Relying on speech alone, we might be left wondering what the students were talking about as it was mostly restricted to verbal request for inscriptions or to seek affirmation of drawings or verbal expressions that need to be understood in relation to what had been gestured or drawn on paper. Observing the iconic gestures Sally produced with her finger over the starting compound in a triangular manner coupled with our knowledge of organic chemistry, we may interpret her gestures in this instance to embody the bromonium ion intermediate where the bromine is attached to two carbon atoms through partial bonds. This contrasted with Heidi's metaphoric gesture where she appeared to be holding down an object in her hand. Thus, the students' gestures embodied the intermediate they had in mind (11–14) while visual inscription was used as a means to concretize the structural information of the intermediate expressed through speech and gestures. Hence, based on the gestures produced, Heidi was able to verbally assure Sally that they were on the right track resulting in Sally inscribing the intermediate (15) which followed closely her gestures of the triangular "wing" structure in Fig. 5.6. In summary, the information as revealed through the three semiotic resources indicated that the students' knowledge about the addition reaction was only sufficient to solve the given problem superficially and that they lacked an in-depth understanding of the reaction mechanism.

The implication of this case study is at least twofold. First, it is necessary to raise awareness of multimodality of concepts among teachers and students. Focusing on nonverbal aspects of communication in addition to written and spoken words to construct, persuade, and report may provide teachers with new resources that will enhance their teaching. For example, our findings highlight students' use of gestures for the representation of chemical structures. Therefore, teachers can also use gestures in additional to speech and writings during instructional discourse as a means for helping students visualize chemical structures as part of the scientific modeling process.

Second, assessment practices need to include at least both visual and verbal modes of representation for students. For instance, if the assessment intent is to elicit students' understanding of reaction mechanisms, undergraduate chemistry assessments need to include a variety of activities such as oral examinations and performance tasks in which students can use inscriptions, gestures, or even modeling software in addition to speech to explain chemical phenomenon. In this way, students are provided with more opportunities to present their knowledge using a variety of modes. Reliance on written examinations confines students to the use of only writings and inscriptions. However, by providing students more opportunities to "talk chemistry," teachers can pay attention to their students' gestures and verbiage in addition to writings to assess scientific ideas of the students.

In the same vein, students may be able to better articulate their conceptions and understandings when a multitude of resources such as gestures in addition to speech and writings are made available. Especially when we are interested to develop students' problem-solving skills to rise above the realm of rote algorithmic manipulations into the realm of creative problem solving (Wood 2006), we need to provide opportunities for students to employ some of these nonverbal resources when they are communicating with teachers and peers. Our collection of empirical evidence positions the gestures of Sally and Heidi explicated in previous section as not just random acts of hand-waving. Their gestures embodied their thoughts which led to the accomplishment of their task. This also lends further support to the argument that gestures are meaning-making resources which students can rely upon to construct and communicate scientific concepts (Goldin-Meadow and Wagner 2005; Pozzer-Ardenghi and Roth 2007).

5.7 Conclusion

In summary, through a close examination of how two students engage in solving organic chemistry problems, the cognitive focus on students' learning (Johnstone 2000; Johnstone and Kellett 1980) is broaden to include a multimodal view of problem solving. This perspective positions students' engagement with scientific tasks as an accomplishment through coordination of semiotic resources where students are engaged in the process of using and the reshaping of resources (Kress et al. 2001). This has potential to unveil what students have in mind, which also in turn shapes their subsequent responses. While many teachers emphasize the reporting function of print and visual representations, it is important that teachers also recognize these semiotic resources as cognitive tools to construct and convey scientific ideas.

Therefore, students need to be given opportunities to use multiple representations central to the practices of scientific communication as a way to support, develop, and showcase their understanding of scientific phenomena. This suggestion is congruent with calls for the development of representational skills as part of the chemistry curriculum and the use of these skills to better understand and assess the chemistry knowledge of our students (Kozma et al. 2000).

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