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How ordering concrete and abstract representations in intermolecular force chemistry tasks influences students' thought processes on the location of dipole-dipole interactions

Isaiah Nelsen, Ayesha Farheen, Scott Lewis

Abstract

Representations in chemistry are the tools by which students, instructors, and chemists reason with chemical concepts that are abstract. Although representations are regularly used within the chemistry classroom, there is more to uncover regarding the ways students interact with representations when given chemistry tasks. This study aimed to address this gap in knowledge. In this study, eighteen students enrolled in second semester general chemistry were recruited for data collection. Semi-structured interviews were utilized to observe how students approached a similar set of dipole-dipole interaction tasks when given four distinct representations. Analysis of the data revealed that students' approaches to these tasks were affected by the newly explicit features present within each representation. Additionally, the ordering in which the representations were presented to the students influenced the specific features students took notice of and implemented into their approaches to the tasks. These findings can better inform instruction and future research involving chemical representations such that students will form a solid foundation in working with and pulling relevant information from various representations when solving chemistry tasks.

Purpose of Representational Competence in Chemistry

Representations in chemistry encode abstract concepts that cannot be accessed through direct observation and present them in a way where instructors and students alike can reason about chemical entities and processes (Hoffman and Laszlo, 1991; Talanquer, 2022; Kozma and Russell, 1997). This utility stretches into the practical world of chemistry, where representations can be used to demonstrate symbolic, submicroscopic, and macroscopic relationships (Hand and Choi, 2010; Keiner and Graulich, 2021). Chemical representations make up the backbone of chemistry and are the precursor to chemical practice (Kozma and Russell, 2005). Nevertheless, without representational competence, the information held within chemical representations remains inaccessible. The term representational competence was first introduced to constitute a skillset pertaining to the reflective use of various representations to contemplate, communicate and work with chemical phenomena in terms of imperceptible chemical entities and processes (Kozma and Russell, 2005). Kozma and Russell detail levels of representational competence ranging from viewing representations as depictions to a more reflective and rhetorical use (2005). Representational competence can be defined by skills like the ability to compare different representations and identify the information being communicated in each (Kozma and Russell, 2005). Additionally, students with high representational competence can map features of one representation onto one another and explain their relationship. Another more practical skill described by Kozma and Russell involves utilizing representations and their features to support claims and make predictions about perceivable chemical phenomena. In these instances, students must also carry the ability to generate or elect appropriate representations for what they are attempting to communicate (Kozma and Russell, 2005). Many studies have been conducted targeting different dimensions of students' representational competency skills (Scheid et al., 2018; Hubber, Tytler, and Haslam, 2010; Wu and Rau, 2018; Chittleborough and Treagust, 2007). While the authors of these studies claim to see a clear correlation between representational competence skills and chemistry content knowledge and learning, opponents counter that the relationship is not clear cut, and there are other factors that must be considered (Stieff and DeSutter, 2021; Sim and Daniel, 2014; Edelsbrunner et al., 2023). Edelsbrunner and colleagues argue that while there is a substantial relationship between content knowledge and representational competence, the two constructs were found to be statistically

separable and may be distinguished by additional constructs like prior conceptions or affective-motivational factors (2023).

Consequently, it can be argued that representational competence is not synonymous with content knowledge in chemistry. While it is true that students with little content knowledge would need more guidance when navigating representations (Cook, Wiebe, and Carter, 2008), researchers have reported that students with comparable levels of content knowledge still perform differently on chemistry tasks when they have different levels of representational competence (Sim and Daniel, 2014). Representations hold many encoded explicit and implicit features that work together to communicate vital information about the nature, behavior, and structure of a molecule or reaction. The explicit features are the properties in a representation directly portrayed while implicit features are those that can be deduced from the explicit features provided. Prior to applying content knowledge to a given chemistry task involving a representation, individuals must "unpack" the representation so that all relevant explicit and implicit features can be considered (Talanquer, 2022). The concept of unpacking was first utilized in the chemistry context as a teaching practice employed to give rise to opportunities for students to extract and focus on the most critical features within an object of learning (Patron, Linder, and Wikman, 2021). The definition of unpacking was later expanded to encompass any individual (i.e. students) undergoing the process of identifying relevant and explicit features that can be used to activate and integrate varying pieces of knowledge (Talanquer, 2022). For the purposes of this study, unpacking will be defined in the more general sense, referring to student processes. The unpacking process is highly dependent on the chemistry task and the representation. The importance of features held within a representation are contingent on how these features relate to the chemistry task at hand. For instance, if a student is given an image of a ball and stick model of methane and asked to determine its geometry, it would be essential to extract the number of atoms and the connectivity of these atoms from the representation. It would be less productive to approach the task by unpacking features like the size of the atoms within the representation.

Student understanding and their subsequent unpacking approaches for representations, however, can be influenced by how the instructor chooses to present and unpack a representation when instructing. In observing the different ways that chemistry instructors choose to unpack representations when lecturing, one study discovered that not all representations were adequately expounded upon by the instructors (Patron, Linder, and Wikman, 2021). Many were found assuming students understood what the features in the representations stood for, while others used verbal explanations with little to no graphical context for what they were describing. In other instances, instructors were presenting representations to students in class and informing them that they could spend time outside of class to develop a deeper understanding of the concept depicted in the representation (Patron, Linder, and Wikman, 2021). Any of these instances can propagate confusion in student understanding of the representation and the concept being taught. Additionally, a lack of intentional training in unpacking representations can lead to difficulty in more advanced chemistry courses that also utilize representations.

Problems with Unpacking Representations

The process of unpacking is learned and requires students to hold knowledge of chemical terminology, patterns and classification systems that are often found in representational structures. (Talanquer, 2022). Problems emerge in students' abilities to work with representations and understand chemical concepts when they have not been trained to properly unpack a representation. These problems can stem from unfamiliarity with a specific representation and insufficient knowledge on how two representations relate to one another (Head, Bucat, Mocerino, and Treagust, 2005). The latter has seemed to be an issue for general chemistry and organic chemistry students alike. In both courses, challenges have been established with students identifying and utilizing the explicit features in one

representation to generate alternative representations (e.g. Cooper, et al., 2010; Sandi-Urena, et al., 2019; Gkitzia, et al., 2020). This aspect of the unpacking process is essential if students wish to make connections between representations and find meaning in highly symbolic representations (Talanquer, 2022). Talanquer defines highly symbolic representations as chemical representations that hold information that must be unpacked to draw connections to other representations (2022). The chemical formula is an example of a highly symbolic representation and is used at large throughout all disciplines of chemistry curriculum.

Without knowledge of how to unpack a chemical formula, students are left with chemical symbols to reason with. Two studies discovered that students ranging from organic chemistry to graduating seniors had trouble when they were asked to generate a Lewis dot structure from a given chemical formula (Cooper, et al., 2010; Sandi-Urena, et al., 2019). These students were found "adorning" chemical symbols with electrons, without an indication that they understood the purpose of the electrons in the Lewis dot representation (Sandi-Urena, et al., 2019). As a result, students crafted Lewis dot structures with nitrogen and oxygen atoms with insufficient or expanded octets (Cooper, et al., 2010). A similar phenomenon was observed in transformational tasks involving alternative representations, such as chemical formula and ball-and-stick representations, where challenges were observed when students were tasked with interpreting the features from a representation and assessing how the features could be used to formulate the structure of a new representation (Keig and Rubba, 1993). Consequently, connections between features in each representation were not made and students invoked marginally relevant information when generating new representations. (Keig and Rubba, 1993). When students do not identify and utilize the explicit cues (atom identity, connectivity, etc.) in a representation, their approaches to chemistry tasks diversify and heuristics can occupy the forefront of their reasoning (Cooper, et al., 2013).

While unpacking representations in chemistry is a necessary skill, the process is no easy feat, especially for novices that are simultaneously learning how to navigate chemistry concepts. To understand the relationships between the structural components of a representation and their inherent properties, students must delve deep into the underlying concepts of chemistry (Cooper, et al., 2013). Even the simplest concepts can appear complicated when they are encoded in a representation. It can be even more difficult for students when they are presented with a set of representations conveying different features. Students must not only distinguish the explicit features in each representation, but they must identify the implicit features that are not portrayed. The density of both explicit and implicit features can vary from representation to representation, making it more difficult to identify the features in the representation that are relevant to the task at hand (Talanquer, 2022). This concept is exemplified in the differences between the Lewis dot structure and the ball and stick representation. While both show the connectivity of atoms within a molecule, only the Lewis dot structure portrays lone pairs. Alternatively, the ball and stick representation depicts the relative sizes of atoms along with the overall molecular geometry. If students are never instructed on these differences, it can be difficult to discern whether a perceived feature on a representation can be taken at face value (e.g. molecular geometry portrayed in Lewis dot structures). It is also important to note that the ball and stick representation and the Lewis dot structure are on two distinct representational levels when considering Johnstone's triangle of chemical knowledge (Johnstone, 1993; Taber, 2013). The Lewis dot structure can be categorized as symbolic while the image of a ball and stick model is a submicroscopic representation. Researchers report student difficulty when working with representations in these distinct levels (Keiner and Graulich, 2021; Treagust et al., 2003; Xu, 2021). Treagust and colleagues uncovered that students do not always apprehend the utility of submicroscopic and symbolic representations that is assumed by the teacher in instruction (2003). Xu expanded on this study and presented an intervention where macroscopic level representations were introduced to students alongside the submicroscopic and symbolic levels (2021). However, during the application portion of this study, students only interacted

with macroscopic and symbolic representations, forgoing a link to the submicroscopic level (Xu, 2021). As a result, teachers cannot assume that utilizing multiple levels of representations in the classroom will translate to students' ability to make connections across representational levels.

Consequently, if some form of intervention is not introduced into instruction, students may fixate on only representational surface features (features that are explicit in a representation) when approaching a task. This phenomenon was observed in a study that asked students and instructors to organize various general chemistry concepts encoded in distinct representations into groups (Kozma & Russell, 1997). The researchers discovered that while instructors created groups based on overarching chemistry principles, chemistry novices formulated groups that dealt with surface features like molecular size (Kozma & Russell, 1997). A similar study requiring students and instructors to categorize organic molecules of the same representation during different points of the semester found that structural features were more commonly used by students as markers for categorization at the beginning of the semester when they were focused on functional groups within their course content. The instructors, however, elected more stereochemical and functional properties to group the organic molecules (Domin, et al., 2008). One of the main causes of students' organization is the lack of exposure to different representations and their utility. This lack of exposure has been attributed, in some instances, to a gap in teacher understanding of multiple representations and the absence of implementation of diverse representations in instruction.

Researchers surveying schools throughout a province in Indonesia uncovered that nearly half of its chemistry faculty were not knowledgeable on the utility of multiple representations within chemistry (Widarti, 2021). Additionally, of the teachers that demonstrated an understanding of multiple representations, approximately one fifth of the teachers implemented multiple representations into their curriculum (Widarti, 2021). In instances where teachers implement multiple representations into chemistry lessons, it has been observed that some instructors hold the assumption that students are already knowledgeable on the implications of implicit and explicit features in the representations (Patron, et al., 2021). Moreover, the textbooks currently in use in chemistry courses fail to provide proper conceptual information for the representations it introduces. Many of the representations mentioned in a textbook are not integrated into the textbook's problem sets, leaving students confused on their utility (Gurung, et al., 2022). Consequently, students tend to employ the representation they are most familiar with, while other types of representations are unused (Kozma and Russell, 1997). Studies have shown that this is not beneficial to the proficiency of students in chemistry. In one study, students who construct and utilize multiple representations when assigned tasks tend to be more successful problem solvers that provide quality arguments for their claims (Bodner and Domin, 2000). In another study, students in organic chemistry laboratories that use more representations to communicate their results produced more well-rounded arguments (Hand and Choi, 2010).

Prior to implementing an intervention to meet this gap in student representational competence, however, we must first identify how students are currently interacting with representations when given chemistry tasks. Currently, the literature quantitatively explores how student approaches differ on similar tasks when given distinct representations (Farheen and Lewis, 2021), where each student was randomly assigned a representation (e.g. Lewis dot structure, space filling models) of the same molecule and given an identical set of multiple-choice questions. The results indicated that the type of representation cued students to differing features and conventions, and influenced students' likelihood to make correct predictions involving chemical properties. An additional study within physics education quantitatively explored the impact of representations on students' answers to conceptual questions. The researchers took additional interest in how consistent students were on similar tasks across three different representations. Their findings, however, yielded the conclusion that there was no significant effect of representations on students' scores (Susac, et al., 2023). Although each of these studies contribute to a more enriched understanding on the relationship between representational competence

and student performance, the way in which specific features present in varying representations impact students' method of unpacking and their understanding of encoded information remains relatively unexplored qualitatively. Data collected from the current study carries the potential to inform instructors and researchers on how changes in representational features directly affect student understanding of chemical concepts and may call for a reassessment of how these representations are utilized and depicted within the classroom.

Student Understanding of Intermolecular Forces

The topic being explored in this study in conjunction with the influence of representations is intermolecular forces. This is a preliminary concept that students are taught during their time in general chemistry and is foundational for many of the subsequent concepts covered in future courses. Representations are inherent in the instruction of intermolecular forces, stemming from their ability to provide detailed depictions of molecular interactions that are directly unobservable. Research conducted on student understanding of intermolecular forces has generally involved intermolecular forces in the context of boiling points and their relative strength to one another (Henderleiter et al. 2001; Schmidt, et al., 2009). One study found that students often generalize principles associated with intermolecular forces such that any molecule with either nitrogen, oxygen, or fluorine carries the ability to hydrogen bond (Schmidt, et al., 2009). Henderleiter and colleagues observed a similar phenomenon in which students conflated chemical concepts to ascertain the functionality and application of hydrogen bonds (2001). Upon reviewing these studies, Cooper, Williams, and Underwood elected to take a different approach and aimed to measure students' understanding of intermolecular forces, rather than focusing on the applications of intermolecular forces (2015). In their methods, they asked students to draw out and write an explanation for their answers to a question involving the location of the hydrogen bonds within three identical molecules. The depictions of the hydrogen bonds consisted of Lewis dot structures with symbols to delineate interaction. The results suggest that a large portion of the students believed that intermolecular forces were within a single molecule rather than between (Cooper et al., 2015). This finding reflects observations made in Peterson and colleagues' (1989) study where students also described intermolecular forces occurring within a molecule. Additionally, it was easier to interpret students' drawn answers than their written answers because of the ambiguity in their written descriptions. Similar findings were uncovered in work involving students' conceptions of London dispersion forces, where students' drawings portraying the mechanisms behind London dispersion forces were far more intricate than their written responses (Becker, et al., 2016). With these findings in mind, the current study aims to investigate how varying representations influence how students approach identifying the location of dipole-dipole interactions.

Theoretical Framework

According to the Multimedia Learning Theory, external representations serve the purpose of standing for concrete objects and abstract concepts (referents) (Rau, 2017; Mayer, 2011). The process a student undertakes when they begin to unpack relevant information from a representation and organize it in the context of a task is known as the conceptualization of an internal representation. Once this internal representation is crafted, the student can begin to draw from content stored in their long-term memory and formulate a mental model on how to solve the task at hand (Rau, 2017). The study of this process is termed semiotics and involves the analysis of signs and their role in meaning making (Pham and Tytler, 2022). According to Peircean semiotics, the meaning making process with signs can be encapsulated by the interaction between three elements; (1) the concept being represented, (2) the representation created, and (3) the interpretation of the representation (Peirce and Buchler, 1902). In

the context of semiotics, these created representations can be defined as symbolic resources developed within a discipline to communicate knowledge (Pham and Tytler, 2022). The representations utilized in chemistry are no exception to this definition and communicate discipline specific chemical concepts through signs that must be interpreted. To access chemical concepts being represented, students must possess both representational competences to unpack the features within the representation and knowledge of the concept being represented (conceptual knowledge) to form an accurate interpretation of the representation. However, as discussed previously, the relationship between conceptual knowledge and representational competences may represent unique characteristics (Edelsbrunner et al., 2023). If students retain representational skills yet are without conceptual knowledge, information pulled from the representation cannot be contextualized. Conversely, simply having conceptual knowledge without representational skills does not guarantee students will correctly unpack relevant representational information and draw connections to content knowledge in the meaning making process (Sim and Daniel, 2014). The semiotic resources, or explicit features, available for students to interpret, vary across the representations in chemistry and require representational skills for the proper unpacking.

If a student unpacks the information encoded in the representation in a means that is not intended, they will not form accurate internal representations. As outlined by Schönborn and Anderson, the type of the representation can be a major determining factor on whether the student forms an accurate internal representation or not (2009). According to dual-representation theory, it has been observed that individuals tend to pull relevant information from representations more accurately when the representation is more abstract than concrete (DeLoache, 2000). Concrete representations offer a greater number of explicit features that are relatively close to the referent while abstract representations are more implicit in nature. Talanquer describes a similar theory, in which the representations commonly used in chemistry can be placed on a spectrum from least unpacked to most unpacked (2022). These categories in this spectrum are delineated by the number of explicit features present in a representation that reflect their real-world referent. The least unpacked representations have many implicit features and can be considered abstract; the most unpacked representations have fewer implicit features and are concrete. As individuals traverse up the spectrum to the more unpacked representations many implicit features become explicit, through the addition of symbols and icons. For example, when transitioning from a chemical formula to a Lewis dot structure, both bonds (in the form of lines) and electrons (in the form of dots) become explicit. Talanquer (2022) poses that the more unpacked a representation is, the greater the number of features students must sort through. When working with these representations in conjunction with a task, it can be difficult to distinguish the features relevant to the task and those that are not. DeLoache (2000) holds a parallel viewpoint in which individuals tend to have a difficult time discerning which features are conceptually applicable to the task at hand when presented with a concrete representation. Therefore, it is a point of interest in this study to observe how the abstract (less unpacked)/concrete (more unpacked) nature of representations impact students' ability to unpack and identify relevant features that can be integrated into their internal representations.

Rationale

To potentially conceptualize more detailed comparisons of representational influence, it is beneficial to qualitatively analyze how the same set of individuals approach similar tasks when presented with varying representations. Presently within literature, investigations have qualitatively explored student ability to translate multiple types of representations that have varying levels of concreteness and abstractness (Keig and Rubba, 1993; Talanquer, 2022). It is important that we broaden

our understanding of how students utilize different representations when approaching tasks that go beyond translation. This representational skill is described by Kozma and Russell as the ability to utilize representations and their features to make predictions or defend assertions made about chemical phenomena (2005). Little research has been conducted on how students approach a sequence of identical chemistry tasks with varied representations. This study ventures into this thought and aims to survey how representations impact students' method of unpacking when approaching a task involving the prediction of dipole-dipole interactions. It is also of importance to assess how the level of abstractness of the representations may influence how students unpack and approach chemical tasks. As students progress from abstract to more concrete representations (or vice versa), it is essential to establish whether the changes in explicit and implicit features are promoting change within students' unpacking and approaches to the chemical tasks. Understanding how students' unpacking approaches change across representations can inform the order in which instructors choose to introduce representations, how instructors introduce each representation and what attention should be given to explicit and implicit features to promote successful student unpacking of representations. With this in mind, the following research question was formulated to guide this study: How does altering the order of representations in a series of similar dipole-dipole interaction tasks influence how students unpack representational features in their approaches to each task?

Methods

Research Setting and Participants

This study was conducted at a research-intensive university in the southeast region of the United States. This study relied on student interviews to explore students' conceptions. Second semester general chemistry students were recruited from a pool of 1369 students enrolled in one of seven classes. All seven classes utilized the same syllabus, textbooks, homework assignments, and exams. The topic of dipole-dipole interactions was selected due to its relevance to the current content students were learning in their general chemistry courses. The timepoints of the interviews ensured that students had received instruction and assessment on molecular polarity and intermolecular forces. Upon analysis of exams and lecture slides, it was determined that students were predominately exposed to and assessed using chemical formulas or Lewis dot diagrams. The pool of students was divided into groups and each group was sent a message calling for volunteers. Students that responded to the message and indicated intent to participate were enrolled in the study. Eighteen students were interviewed.

Ethical Considerations

Local regulations stipulate that approval by an independent review board be attained prior to data collection. Study procedures were reviewed and approved by the Institutional Review Board at the research setting as Pro00020840. To minimize potential appearances of coercion, personnel sending the recruitment messages and conducting interviews were not involved in instruction of the classes where recruitment occurred. Prior to participation, students were provided a written informed consent document detailing the procedures for the study, the voluntary nature of the study, and the right to withdraw at any time. Each participating student consented to the study and received a 25-dollar gift card as compensation for their participation.

Data Collection

The interviews were 30-60 minutes, semi-structured, and conducted in person. Interviews were conducted one-on-one with each participant by either the second author or an undergraduate researcher recruited for the data collection process. In this study, the term semi-structured interview is

used to describe a process where there is a set list of tasks and follow up questions are dependent on student responses. This method was chosen to capture each participant's unique approach to the tasks. The students were presented with four sets of molecules and asked to predict the location of the dipole-dipole interaction between the two molecules in each set. For each set of molecules, students were given the following prompt "Imagine the following two molecules are in a solution next to each other. The strongest intermolecular force between them is dipole-dipole. Identify the pair(s) of atoms where the strongest intermolecular force would occur? Draw a dotted line connecting these atoms." Students were provided the electronegativity values of atoms in each task. The participants viewed the tasks on an iPad and used an electronic pencil to indicate the location of the dipole-dipole interaction in static images of molecules. They were also instructed to record any information or observations that would aid in their task-solving process. The iPad was chosen as the delivery vehicle for the protocol in this study due to its convenience for data storage. The interview was audio recorded and all information recorded on the iPad by the students was screen captured. Each task consisted of two distinct molecules and a different type of representation. The type of representation for each set was chosen based on varying levels of abstractness. The four representations utilized in this study were chemical formula, Lewis dot structures, ball and stick, and space filling.

Two protocols, versions 1 and 2 presented in Figure 1, of the interview were formulated so students would receive one of two opposite gradients of representational abstractness. Version 1 decreased in abstractness as the student transitioned from one task to the next. Students who received Version 1 were presented with the chemical formula representation first and worked their way to images of space filling models. Version 2 of the protocol increased in abstractness as the interview progressed, beginning with images of space filling models and ending with chemical formula. Nine interviews were carried out for each version of the protocol. Participants engaging in Version 1 were given a pseudonym beginning with the letter S; participants engaging in Version 2 began with the letter R. Each version had the same pair of molecules in the same order. The identity of the molecules and their order is as follows: 1. sulfur dichloride and ammonia, 2. tribromo silane and hydrogen cyanide, 3. iodine monofluoride and selenium dioxide, and 4) chloromethane and hydrogen bromide. These molecules were selected on the basis of several factors. Firstly, each molecule retained a single center atom. Each molecule selected in the tasks was also polar covalent based on electronegativity values, ensuring that dipole-dipole interactions are possible between the two molecules in each task. Lastly, the geometry of the molecules utilized varies throughout, verifying the students are not just dealing with one type of geometry in all four tasks.

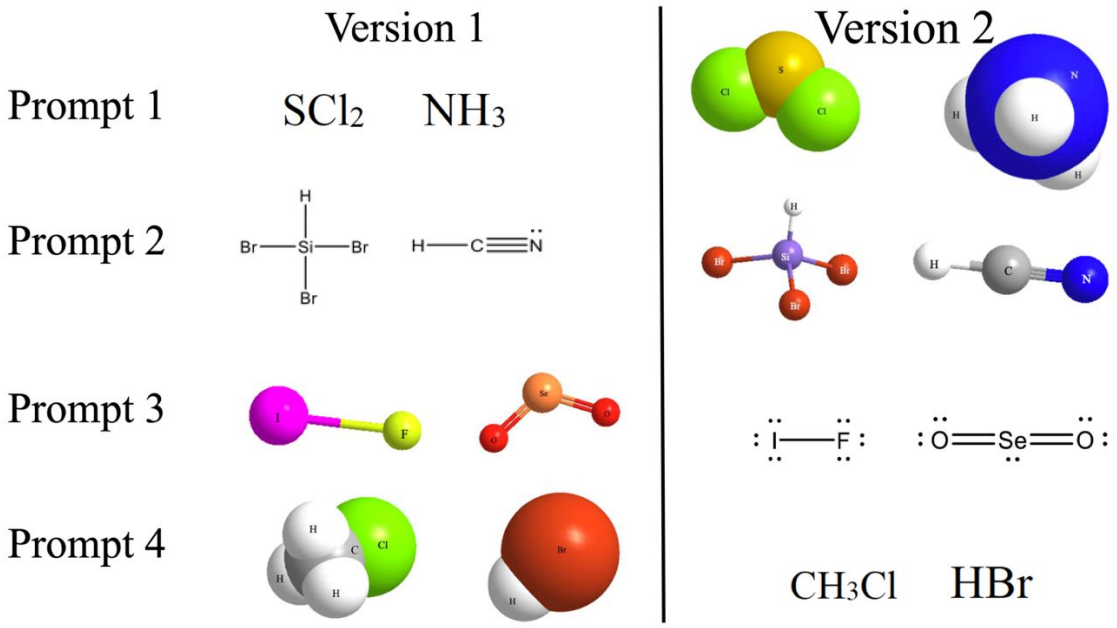


Figure 1 Molecular representations utilized within each version of the protocol. The different gradients of abstractness (level of unpacking) are displayed.

Data Analysis

Upon completion of the interviews, four audio files were transcribed manually, and the remaining audio files were transcribed first using software that converts talk to text and then reviewed manually for corrections. Transcription was done with the target of a verbatim capturing of the audio files; the screen captures from the iPad were embedded into the transcripts of each interview. The transcripts were examined by the first and second authors for patterns in unpacking approaches when determining the location of the dipole-dipole interaction. We were specifically looking for the explicit and implicit features that students were employing during each task. Additionally, flow-charts were constructed by the first author to trace the explicit and implicit features that students unpacked as they transitioned from one representation to the next. The completed flow charts were presented to the second and third authors, along with excerpts from the transcripts, to ensure the flowcharts accurately represented the themes present within the transcripts. Thereafter, codes were inductively generated by the first author based on the representational features and operations (translation) students were utilizing throughout the set of 18 transcripts. In this study, features can be defined as the chemical properties that are either explicit (e.g. lone pairs in a Lewis dot structure) or implicit (e.g. relative size of atoms in a Lewis dot structure) in the representation that students use in their approaches. Operations are processes that students may employ in an attempt to extract these features. An iterative process of code development, code application, interrater checking, discussion, and code revision was applied to reach a set of codes that were representative of the data. Using the finalized codebook, presented in Table 1, consensus coding was carried out to finalize the coded transcripts. The coded transcripts were analyzed and organized into a table based on the representation the students were working with and the protocol version they received, presented in Tables 2 and 3. This allowed us to compare the codes across representations particular to each version and determine how students altered the features or operations they unpacked from each representation. The codes were then analyzed to identify the features or operations that students enlisted and the ones they relinquished in their approaches as they

worked with each representation. To illustrate, if students unpacked and utilized lone pairs for the task involving the Lewis dot structures but focused on atom size when presented with the images of ball and stick models, the lone pairs would be the relinquished feature and size would be the enlisted feature. The results from both versions of the protocol were then compared to one another to determine the potential impact that level of representational abstractness had on student unpacking. A separate analysis of the same data set on variations in students' usage of electronegativity in locating the dipole-dipole force has been published elsewhere (Farheen, et al., 2024).

Table 1: Description of final codes that were assigned

Codes	Description
Electronegativity	Student utilizes electronegativity values or mentions electronegativity as reasoning for the location of the dipole-dipole force
Geometry	Student mentions the molecular geometry or shape of the molecule. Student may use this as an explanation for the presence of a dipole-dipole interaction
Lone Pairs	Student identifies lone pairs and cites their impact on geometry and the overall dipole-dipole moment.
Open Site or Octet	Student mentions a molecule "lacking an octet" or "retaining an open space" that needs to be filled. Student may cite a lone pair as a site that's "available" or "needs a bond"
Size of Atom	Student mentions the size of the atom as a factor to consider in determining dipole-dipole location.
Translation	Student redraws the structure as an alternative representation of the same molecule
Valence Charge	Student utilizes ionic or valence charge as a means to determine the location of the dipole-dipole force.
Bond Order	Student makes a connection between intermolecular forces and the number of bonds

Results

Upon analysis of the 18 interviews, several changes in unpacking arose as students were presented with each task and asked to find the locations of the dipole-dipole moments between the two molecules. The changes occurred as the representation was altered in each task in which students began to identify new features and relinquish previously used features, summarized in Table 2 for Version 1 and Table 3 for Version 2. The organization of the results will first elaborate on the features or operations used for each task within Version 1. Next, the results will be described for each task in Version 2. Finally, a comparison of student approaches in the two versions is presented in the discussion section.

Table 2: Features and operations utilized by students in version 1 for each representation in the dipole-dipole interaction tasks

Version 1	Chemical Formula	Lewis Dot	Ball and Stick	Space Filling
Sarah	Electronegativity Translation	Electronegativity Geometry	Electronegativity	Electronegativity Translation Size
Sam	Electronegativity Translation	Electronegativity	Electronegativity	Electronegativity
Sandeep	Translation Open Site or Octet	Electronegativity	Size	Size
Spencer	Translation Electronegativity Geometry Lone Pairs	Electronegativity Geometry	Electronegativity Size	Electronegativity
Sawyer	Electronegativity	Electronegativity Open site/octet	Electronegativity	Electronegativity Translation
Sasha	Electronegativity Translation	Open site or Octet	Electronegativity	Electronegativity
Sadie	Electronegativity Translation	Open Site or Octet	Electronegativity	Open Site or Octet
Sabrina	Electronegativity	Open Site or Octet	Electronegativity	Electronegativity Open Site or Octet
Sebastian	Translation Open Site or Octet	Open Site or Octet Geometry	Size	Electronegativity

Version 1: Chemical Formula

Sarah, Sam, Sandeep, Spencer, Sawyer, Sasha, Sadie, Sabrina, and Sebatian all worked with the chemical formula representation first when attempting to determine the location of the dipole-dipole forces. The chemical formula generated consistent unpacking approaches across almost all students. Students began by translating the chemical formula into a Lewis dot structure and proceeded to utilize the electronegativity values to determine the location of the dipole-dipole forces. Only two students elected not to translate the formula (Sawyer and Sabrina) into a Lewis dot structure. As depicted in Figure 2 in the image on the left-hand side, these students worked with the electronegativity from each element to discern where the dotted line representing dipole-dipole interaction should be drawn between the two chemical formulas. When asked why they chose not to translate the structure, Sawyer replied “I did feel like I need to draw it out, but I wasn't sure how to.” In addition to the use of translation and electronegativity, three students discussed approaches to the task that resulted from their translation of the chemical formulas. During the translation of the ammonia molecule, Sandeep omitted the lone pairs and identified it as an open spot. As a result, he concluded that the open spot was the location of the dipole-dipole interaction as depicted in Figure 2 (right hand side). Sandeep explained “It definitely connects to the nitrogen because that one has the open spot and it's more electronegative, so connect that to chlorine because that's also the most electronegative.” Sebastian came to a similar conclusion, by following a separate line of logic. This student was successful in identifying the implicit lone pairs on ammonia but insisted that lone pairs generated destabilization;

therefore, the student categorized ammonia as needing an octet and drew the dipole-dipole interaction between the lone pair on ammonia and a lone pair on one of the chlorines.

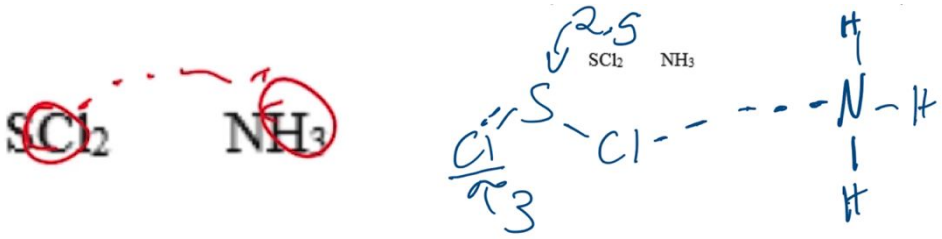


Figure 2: Left: Sawyer elected not to draw the Lewis dot structure and decided the location of dipole-dipole interactions using electronegativity values. Right: Sandeep omitted lone pairs on ammonia and interpreted the open site available for dipole-dipole interactions

Version 1: Lewis Dot

As students continued to the Lewis dot representation, several showed changes in the features they unpacked, which consequently changed their approach to the task. Although all students still recognized electronegativity, many of the newfound explicit features seemed to impact the way in which they justified their answers for dipole-dipole interaction location. Four students (Sawyer, Sasha, Sadie, and Sabrina) that did not take lone pairs into account for their explanation in the chemical formula question, identified the now explicit lone pairs in the Lewis dot structure and cited them as reasoning for their choice in dipole-dipole location. Along with Sebastian, these four participants claimed that the lone pairs represent sites that are free to bond with other atoms. Sadie cited nitrogen's role in dipole-dipole interactions and supported this assertion with the following explanation: "because carbon, it has four already and then hydrogen can only have one. And so, nitrogen, there's the two electrons right there, they can bond." Sasha, Sabrina, and Sebastian provided similar logic, illustrating a dipole-dipole interaction connecting either bromine or silicon to nitrogen as depicted in Figure 3. Further into the interview, Sawyer recognized the contradiction between this approach and the electronegativity values. He explained "Nitrogen is the only one with the free pair of electrons. However, their electronegativity difference is only 0.2 (between nitrogen and bromine), which would not make it polar." Conversely, the presence of lone pairs elicited Sandeep to realize a dissonance with the approach used on the prior representation: "My basis on this other one (Chemical Formula) was them having openings for connecting and all of these are already paired. I can't use that as my basis anymore...The carbon already has four and nitrogen is already fulfilled, and it wouldn't need to interact with anything else." In this case, the lone pairs from the representation prompted the student to abandon the approach utilized in the previous task of identifying open sites in the molecules and instead brought forth the use of electronegativity. Another feature that students took notice of when presented with the Lewis dot representation was geometry. Sarah and Spencer were the two most prominent examples of this observation. As Sarah worked her way through the prompt, she began to discuss the polarity of the molecule, bringing forth the topic of geometry. Sarah explained "it's all coming back... I do know that if you do look at the geometry, then you will be able to tell whether it's polar or nonpolar." Spencer followed a similar path and went a step further, emphasizing the symmetry of the molecule and how it impacts polarity. Lastly, it is important to note that almost all students abandoned translation as a means for unpacking the representations. When students were asked why they did not translate the structure for the Lewis dot Representation, they answered that the structure they needed was already provided.

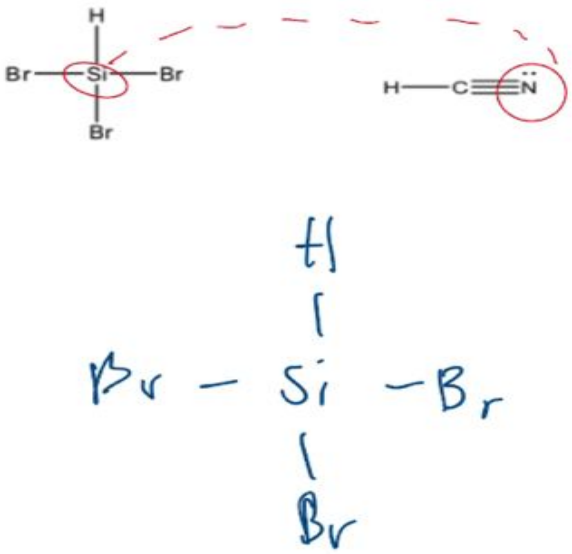


Figure 3 Pictured above, Sasha identified the lone pairs on nitrogen as her deciding factor in her approach to the task. Sawyer, Sasha, and Sabrina all unpacked the representation similarly and highlighted the importance of the lone pairs when determining dipole-dipole interaction.

Version 1: Ball and Stick

As the protocol shifted focus to the ball and stick representation, four students (Sawyer, Sasha, Sadie, and Sabrina) returned to their approach with the chemical formula representation and utilized the electronegativity values. Usage of open site and geometry were no longer the point of emphasis for any of the students. Instead, the two primary features utilized rested in size or electronegativity. Six students (Sarah, Sam, Sawyer, Sasha, Sadie, and Sabrina) homed in on approaches that focused on electronegativity values rather than representational features. Three students (Sandeep, Spencer, and Sebatian) began to observe the various sizes of atoms within the ball and stick representation. At the outset, these students were taken aback by this novel feature in the ball and stick representation. Upon observing the representation, Sandeep stated “I really have no idea what's going on.” Eventually this student connected the two biggest atoms (Selenium and Iodine) stating that the size signifies attraction between two molecules. Sebastian carried a similar conception, however, with inverse implications stating “The bigger the two atoms that are bonding are, the weaker the forces are.” Spencer elected an approach that utilized both electronegativity and size. Although this student initially focused on size, he noticed the high electronegativity of fluorine and recognized his approach as contradictory. Therefore, Spencer designated two dipole moments, one in which fluorine carries the partial negative charge due to its high electronegativity and one where selenium carries the partial negative charge as a result of its size (Figure 4). Several students, including Sam and Sawyer, also recognized the different sizes of the atoms, yet were deterred from this approach after surveying the electronegativity values of the atoms. Sawyer put forth “Usually, if the atom is bigger, it forms a stronger dipole,” possibly invoking the trend with atomic size and the strength of London dispersion forces. Nevertheless, after further consideration the student elected to make electronegativity the central reasoning for the location of his dipole-dipole interaction.

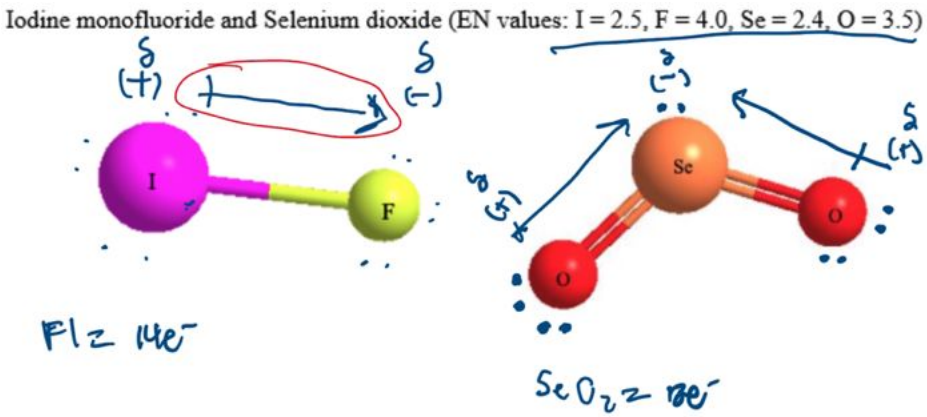


Figure 4 Spencer utilized both size and electronegativity to determine the dipole moments. The dipole between iodine and fluorine was based on electronegativity while the dipoles between selenium and the oxygen atoms were based on size.

Version 1: Space Filling

In progressing to the space filling representation, only one student stayed consistent in the use of size. Sarah, Sam, Spencer, Sawyer, Sasha, and Sadie all used the electronegativity values provided to them in some fashion. Several of these students recognized the size difference between the atoms in the space-filling representation yet discerned this distinction as misleading and not the correct way to determine the location of the interaction. Spencer described his model stating "I think it's just because seeing how one ball can be bigger than the other throws you off easily." Although Sarah predominately employed the electronegativity values provided, the student noticed that the sizes of atoms in the space filling representation correlated with the magnitude of their corresponding electronegativity values. To verify the student's position, she was asked whether size relates to electronegativity, to which Sarah responded "In this model, yes." The only student that stayed consistent with the size approach between the ball and stick and space filling representation was Sandeep. Immediately after Sandeep observed this representation he made a connection with the previous representation and explained "I feel like this one goes off the last one of just wanting to make the bigger ones connect." The student proceeded to draw a line signifying the dipole-dipole interaction between the largest atoms in each molecule of the representation (Cl and Br). Two students (Sadie and Sabrina) reapplied the unpacking approaches they used when presented with the Lewis dot diagram. Both students surveyed the connectivity of the representation and expressed difficulty in distinguishing the bonds within the molecules. Sarah and Sawyer faced similar issues in decoding the representation and chose to translate the space filling representation to the Lewis dot representation for clarity of bonds and lone pairs. However, Sadie and Sabrina did not translate the representations and began to look at the octet of each atom, surveying for any open sites. After establishing that hydrogens and carbon's octet was full, the students speculated that chlorine and bromine retained open spots that made it possible for bonding. As Sabrina explained, "its either chlorine and bromine or carbon and bromine. Judging by how carbon has very few bonding sites, I believe that chlorine and bromine is where there's dipole-dipole." This approach differed from the Lewis dot representation because students were not able to observe lone pairs, as they were not provided in the images of the space filling models. Therefore, Sadie and Sabrina interpreted the space filling diagrams, where lone pairs were implicit, as open spots in the octet of chlorine and bromine.

Table 3: Features and operations utilized by students in version 2 for each representation in the dipole-dipole interaction tasks

Version 2	Space Filling	Ball and Stick	Lewis Dot	Chemical Formula
Ralph	Electronegativity	Electronegativity	Electronegativity	Electronegativity Translation Geometry
Roger	Geometry Translation	Geometry	Geometry Lone Pairs	Translation Geometry Lone Pairs
Ria	Electronegativity Valence Charge	Electronegativity Bond Order	Electronegativity Open Site or Octet	Electronegativity
Regan	Electronegativity	Electronegativity	Electronegativity Geometry Lone Pairs	Translation Electronegativity
Rachel	Valence Charge	Electronegativity	Electronegativity Geometry Lone Pairs	Translation Open site/Octet
Rebecca	Electronegativity Valence Charge	Electronegativity Translation Bond Order Geometry	Electronegativity Geometry Lone Pairs	Translation Electronegativity
Ranger	Electronegativity Translation Geometry	Electronegativity Translation Geometry	Electronegativity Geometry Lone Pairs	Electronegativity Open Site or Octet Translation
Richard	Electronegativity Translation Valence Charge Geometry Lone Pair	Electronegativity	Electronegativity Geometry Lone Pairs	Electronegativity Open Site or Octet Translation
Ruby	Electronegativity	Electronegativity	Electronegativity	Electronegativity Translation

Version 2: Space Filling

The approaches that the students elected to determine the location of the dipole-dipole interaction when beginning with the space filling representation encompassed a variety of features not utilized by students who worked in version 1 of the interview. While the use of size and open site/octet were prevalent in version 1, neither of these features were mentioned by students in version 2. Overall, there were three main approaches that students favored upon unpacking the features in the space filling representation. Similar to Version 1, several students worked with the electronegativity values provided. Although the way in which electronegativity was used varied, Ralph, Ria, Regan, Rebecca, Ranger, and Ruby placed emphasis on how these values could be used to determine the location of the dipole-dipole interaction. Ranger drew dipole moments within sulfur dichloride and ammonia and connected the opposite poles shown in Figure 5. Student approaches in version 2 began to diverge from those seen in version 1 as several students focused on the concept of valence charge. Ria, Rachel, Rebecca, and Richard began assigning charges to each of the atoms in the molecules. When asked

where these charges originate from, the students either provided the explanation that they were from the periodic table, or that they knew these charges were associated with each atom. Once the charges were assigned, these participants proceeded to connect the atoms of opposite charges. Rachel was quick to connect the chlorine and hydrogen molecule, claiming "the first molecule, Cl is negative, the charge and Hydrogen is positive, and they attract each other." Richard adopted a similar approach and when asked to elaborate envisioned a double-displacement reaction, stating "...if you were to write it out, the equation for it out, I guess you could rearrange the atoms so that it would make each-- HCl would be a product." Somewhat similarly, Rebecca posited that the atoms dissociate from one another, and re-bond based on their valence charges and availability for bonding (Figure 6). Rebecca and Ria integrated electronegativity into their approaches, asserting that it was a measure of each atom's attraction to one another. Translation and geometry were two approaches that students used in tandem with electronegativity and valence charge. Roger, Ranger, and Richard all translated the space filling representation into an alternative representation and homed in on the geometry of each of the molecules. Roger was quick to take notice of the geometry of the molecule, asserting that molecules with bent geometry always have dipole moments. The most common representation students utilized when translating was the Lewis dot structure. Students seemed to gravitate towards the idea that this representation allowed them to visualize the lone pairs and observe how they impacted the geometry of the molecule. Ranger made this point in his explanation of why he chose to translate the space filling representation stating, "I guess with this shape; I was trying to see if there were any lone pairs of electrons because I know that usually can indicate polarity."

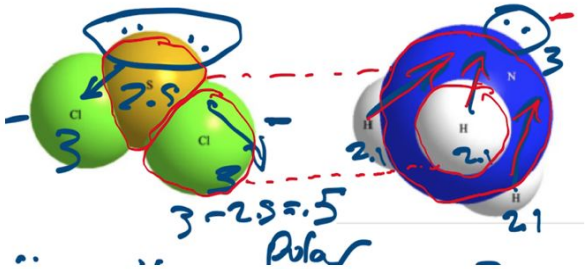


Figure 5 Ranger approached the first task by using the electronegativity values to determine the dipoles and connecting the opposite partial charges

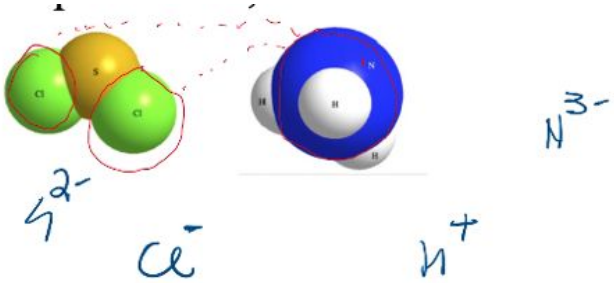


Figure 6 Rebecca assigned valence charges to each of the dissociated atoms. Electronegativity was treated as a measure of attraction between atoms.

Version 2: Ball and Stick

While several changes arose in progressing to the ball and stick representation, many students remained consistent in their approaches. The main change observed was participants' abandonment of valence charge as an approach. Ralph, Ria, Regan, Rebecca, Ranger, Richard and Ruby continued to employ electronegativity values. Rachel joined this group of participants upon transitioning to the ball and stick representation and explained her process of determining polarity stating, "I think I remember now, like, you subtract 2.8 and 1.8 to get one." Geometry remained a significant aspect of several participants' approaches, especially for Roger, who followed his path of logic from the first prompt and was adamant that geometry was the only essential factor in determining polarity and the location of a dipole-dipole moment. While working through prompt 2, Roger postulated "these have like, a very small, like angle. And that, I think, I'm pretty sure that means when you have the intermolecular forces, they're forcing each other to come close together." The other participants that explicitly unpacked the geometry of the molecule and integrated it into their approaches were Rebecca and Ranger. While lone pairs were still implicit in this task, the newly explicit bonds seemed to draw student attention away from the electronegativity values and introduced a new approach not present in the tasks pertaining to the space filling representation. Although Ria primarily concentrated on the electronegativity values as she did in the previous task, the first thing that this participant noticed was the triple bond between the carbon and the nitrogen, asserting that the number of bonds signifies the strength of dipole-dipole interactions in the molecule. Ria noticed "It looks like there's a triple bond that forms between the carbon and the nitrogen. I don't know if I'm reading that right, but it looks like there's three lines" and followed this observation by saying "It means that that's a stronger bond right there and it's harder to break." Rebecca held a similar belief and claimed that the closer an atom was to completing the octet the more affinity it had for a dipole-dipole interaction. She went on to clarify that this affinity was a result of the number of bonds an atom retains.

Version 2: Lewis Dot Structures

The progression to the more abstract Lewis dot representation seemed to solidify many of the participants approaches to finding the dipole-dipole interaction locations. Almost all students, with the exception of Roger, relied on the electronegativity values when given a Lewis dot structure. One occurrence that was observed in student approaches for the Lewis dot structure was the use of lone pairs in deciphering molecular geometry. Six students highlighted the impact that the lone pairs had on the geometry of the selenium dioxide. Initially, however, three of these students carried the assumption that molecular geometry was explicit in Lewis dot structures. Regan, Rachel, and Rebecca drew dipole moments for SeO_2 and designated the molecule as linear and non-polar, without taking into account the influence of lone pairs. Regan explained "It's not polar, actually. The dipole doesn't exist here" citing that the dipoles pulled against each other and therefore cancelled out. Richard almost chose a similar line of logic but reconsidered after recognizing the presence of the lone pair admitting "A spatial arrangement of selenium dioxide makes it seem like it's a linear molecule when it's actually not." Eventually Regan, Rachel, and Rebecca had the same realization and Rebecca presented the following thought: "The lone pair, I'm pretty sure it's going to have a big effect on the bond angle. So, the presence of the lone pairs would make it so that the molecule, instead of being linear, it would look more like something like this (shown in Figure 7). I think in that case, the forces wouldn't cancel out." Roger did not experience the same difficulty that Regan, Rachel, and Rebecca faced in assigning accurate geometry to SeO_2. He first recognized the lone pairs and asserted that they produced a bent geometry in the SeO_2 molecule. In contrast to version 1, only one student referred to the concept of bonding availability in their approach. Ria construed the areas where there appeared to be no lone pairs as openings within the atom's octets explaining "I think the selenium...also needs two pairs of electrons or one pair of electrons." The student's observation was coupled with the concept of electronegativity; as a

result, the student chose to connect the fluorine and selenium due to fluorine's high electronegativity, and selenium's "accessibility."

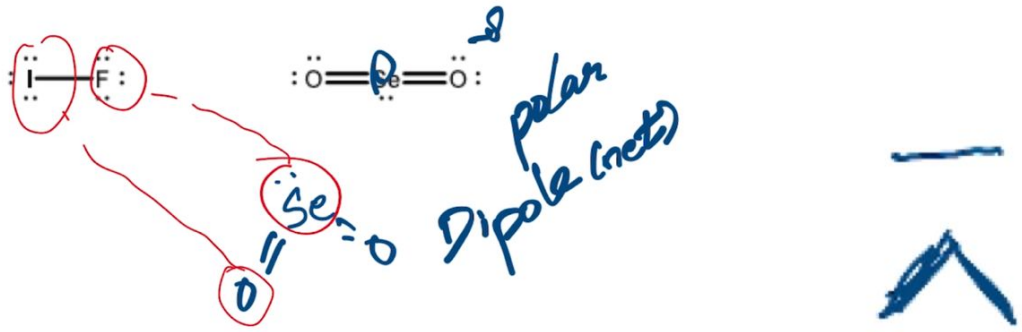


Figure 7 Left: Regan redrew the selenium dioxide molecule to reflect the implicit geometry. Right: Rebecca's depiction of the implicit geometry of selenium dioxide.

Version 2: Chemical Formula

The abstract nature of the chemical formula representation amplified the use of representational translation among participants. Only one student elected not to translate the chemical formula into a Lewis structure. The way in which Ria approached this task did not require translation, in that she strictly focused on the molar masses of the atoms in the molecules. The features of the chemical formula reminded the student of this concept as she explained "I did it with chemical formula because that's normally what we do whenever we're doing stoichiometry. We're always given the chemical formula, and then we always have to find the molar mass of that molecule." Similar to version 1, electronegativity, was the most common approach that students employed when working with the chemical formula. Electronegativity values were used by Ralph, Regan, Rebecca, Ranger, Richard, and Ruby. Initially, Rachel also used electronegativity to determine the dipole moments within each molecule. However, her decision to designate chlorine as the central atom led Rachel to believe that chlorine was incapable of participating in dipole-dipole interactions due to its central position in the molecule (Figure 8). Rachel explained, "I don't know about this one because chlorine is the central… and I don't really know how it's going to connect to the hydrogen." The student proceeded to connect the bromine and hydrogen because of their availability. The idea of bonding availability proved to be a recurring theme in both Ranger and Richard's responses as well. Ranger and Richard were attempting to show dipole-dipole interactions between the central carbon and the bromine but failed to do so because the carbon was centrally located. While referring to the representations depicted in the previous three tasks, Ranger expressed his confusion stating "It's like everything seems readily accessible in all of the other the molecules." Due to this perceived inability to bond, both participants settled on only connecting chlorine and hydrogen, citing their electronegativity differences and accessibility.

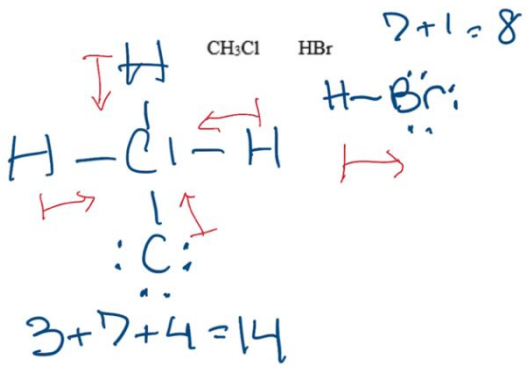


Figure 8 Rachel identified chlorine as the central atom due to its electronegativity value.

Discussion

The Multimedia Learning Theory differentiates between types of representations based on their relative iconicity and symbology (Rau, 2017). This theory suggests that for students to interact with and learn from these representations, they must form accurate internal representations and incorporate them into their mental models of the content (Rau, 2017; Mayer, 2011). Semiotics within chemistry presents a similar notion where students form interpretations from representations meant to convey disciplinary knowledge (Pham and Tytler, 2022). The process by which students develop the skills to use representational features to form accurate internal representations and make predictions about chemical phenomena, however, is not outlined in either of these theories and is difficult to ascertain without first understanding how chemistry students are interacting with these different representations. This study sought to begin the process of building this foundational knowledge, and provided evidence suggesting that the way students interact with different representations in a given chemistry task is not consistent. Prior to exploring the role of the different representations in student approaches to the tasks, however, the connection between representational features and content knowledge in the meaning making process must also be considered. Many of participants carried alternative conceptions of how to identify the location of a dipole-dipole interaction. These conceptions are explored in detail in a previous paper (Farheen, et al., 2024). While the relative difficulty of each task is unknown, an effort was made to maintain the difficulty across tasks by keeping the prompt consistent and only including one central atom in each molecule. Therefore, it is difficult to determine if any one task would require a wider breadth of prior knowledge. However, it can be argued that the conceptions of dipole-dipole interactions students carried may have reinforced the explicit features they chose to unpack. This relationship between prior knowledge and representational competence is best exemplified in Roger's responses to the four tasks. Throughout each task, Roger highlighted the importance of molecular geometry in determining diople-dipole interactions, even when geometry was not explicitly present. Thus, it can be inferred that Roger's prior conception of molecular geometries' relation to dipole-dipole interactions reinforced his use of this explicit feature.

Nevertheless, not all students were bound to a prior conception throughout the tasks, and it became clear that as the representations were altered, students took notice and utilized newly explicit features that generated variations within their approaches. Although electronegativity was the most commonly used feature throughout participants' answers, it is important to note that these values were provided to the students in the prompt. Even when students leaned more toward the features they unpacked from the representations, many established a final decision based on the security that the electronegativity values provided. Ria established this observed phenomenon when he reasoned "I think I'm going to stick with that method because the electronegativity values are in the prompt for a reason, they're not just being given for no reason. I think that does have the most relevance then."

Nevertheless, the use of electronegativity does not preclude the clear influence of the representations. As depicted in Tables 4 and 5, the change in explicit features as the representation was altered appeared to cue the participants to unpack and consider new features in both versions of the protocol. Additionally, the ordering of the representations based on abstractness/concreteness in each version produced contrasting approaches for the same representation type. As the representation was changed for each task, participants in both versions seemed drawn to the newly explicit features. Considering the fact participants in version 2 initially observed the most concrete of the four representations, it should be acknowledged that as they transitioned to the more abstract representations, there were fewer newly explicit features to take note of. The contrary is true for students in version 1, who observed a greater number of newly explicit features as they progressed through the tasks. The impact of these protocol version differences on participants' unpacking of each representation is discussed in detail below.

Table 4 Summary of Changes in Version 1 Students' Unpacking of Features and Use of Operations as Representation was Altered

	Chemical Formula	**Lewis Dot Structure**	**Ball and Stick**	**Space Filling**
Changes in Features and Operations	Electronegativity Translation Open Site or Octet	Geometry ~~Translation~~ Electronegativity Open Site or Octet	Size ~~Open Site or Octet~~ ~~Geometry~~ Electronegativity	Open Site or Octet Translation Size Electronegativity
Text in red= relinquished; Text in green= enlisted; Text in black= consistent				

Table 5 Summary of Changes in Version 2 Students' Unpacking of Features and Use of Operations as Representation was Altered

	Space Filling	**Ball and Stick**	**Lewis Dot Structure**	**Chemical Formula**
Changes in Features and Operations	Electronegativity Valence Charge Translation Geometry	Bond order ~~Valence Charge~~ Electronegativity Translation Geometry	Lone Pairs ~~Bond order~~ ~~Translation~~ Electronegativity Geometry	Open Site or Octet Translation ~~Lone Pairs~~ Electronegativity Geometry
Text in red= relinquished; Text in green= enlisted; Text in black= consistent				

Chemical Formula

The majority of students in both version 1 and version 2 established their approaches in the electronegativity values provided when presented with the chemical formula. The lack of variation between the approaches when compared to the other representations can be best explained by the limited number of explicit features present within the chemical formula representation. The chemical formula can be considered abstract in that the only explicit features within this representation were atom identity and atom count. As a result, students in both versions utilized translation to garner more information about the molecules they were working with. Although translation is considered a skill in representational competence, it is not a skill required for the tasks in this study. This desire to consider "all the information," however, does indicate an attempt to relate the different representational features in the meaning making process. Nevertheless, the features present in their Lewis dot

structures were sparsely emphasized. The cases where students like Sebastian and Sandeep departed from the electronegativity values was when variations in representational translation occurred. Parallel to translational representation studies in the literature, several participants in both version 1 and version 2 of the protocol found difficulty in translating the chemical formula, electing to add or withhold lone pairs (Keig and Rubba, 1993). This produced new information that appeared to be relevant but was a result of a misstep within the unpacking process. While students in version 1 elected to focus on this new information stemming from mistranslation and emphasize open site, students in version 2 were more hesitant to depart from electronegativity as an approach. This can likely be attributed to the ordering effect of the representations in version 2. In version 1 students were beginning to engage in the task of determining dipole-dipole interaction locations during the interview while students in version 2 were more grounded in their approaches from the previous tasks.

Lewis Dot

The explicit lone pairs and connectivity introduced in the Lewis dot structures impacted both students in version 1 and version 2 in contrasting ways. Students in version 1, who had previously used electronegativity in chemical formula, were now discussing the molecules' availability for bonding and the necessity of an octet in a prompt that specifically asked for dipole-dipole interactions between molecules. Seeing the now explicit lone pairs prompted these participants to consider a new internal representation on the relationship between structural features and dipole-dipole interactions. To these participants, the presence of lone pairs could be considered bonding sites that need to be filled, conflating the concepts of dipole-dipole interactions and covalent bonding. This fusion of concepts potentially stems from the emphasis that instructors tend to place on covalent bonding as opposed to concepts like intermolecular forces and represents another example of the relationship between conceptual knowledge and representational competence. Within general chemistry, students receive extensive instruction on the process of covalent bonding with varying types of polyatomic molecules. Conversely, instruction on dipole-dipole interactions tends to involve a select set of molecules that students consistently see. Consequently, when students are presented with a set of unfamiliar molecules with explicit lone pairs, it is more understandable why they may choose to share those lone pairs between the molecules. While students who received version 2 of the protocol also took notice of the lone pairs, they did not consider them open sites and instead implemented them into geometry, which was a feature they utilized in both the ball and stick and space filling representations. Six out of the nine students unpacked the geometry of the molecule, compared to just three students in version 1. Prior to the Lewis dot Structure, version 2 students had worked with two representations that communicated molecular geometry explicitly. Despite geometry not being an explicit feature in Lewis dot structures, it still was an inherent part of their approaches in previous representations, and therefore applicable to this task. Three students within version 2 initially assumed molecular geometry was being explicitly represented and mistakenly designated selenium dioxide as linear and nonpolar, foregoing the impact of the lone pairs on the overall geometry. Although all three students eventually changed their answers to reflect the correct geometry, it is still clear the initial internal representations that they had formulated were founded in the explicit features present within other representations and not in the Lewis dot structures. A similar finding was present in Farheen and Lewis' study where students assumed geometry was explicit in the Lewis dot representation (2021). As detailed in Table 4, students in version 1 were not previously disposed to representational molecular geometry and therefore did not face this issue when working with the Lewis dot structures.

Ball and Stick

The ball and stick representation's explicit depiction of atom size generated changes in approaches for several students in version 1 (Table 4). In this version, atom size was not introduced

until the third task. Consequently, several participants perceived this newly explicit feature as relevant and elected to implement it into their approach as a way of determining the strongest dipole-dipole interaction. Interestingly, students in version 2 of the protocol did not seem to gravitate towards size in the same way and instead focused on either electronegativity or the number of bonds between atoms (Table 4). One plausible explanation for this phenomenon is grounded in the notion that students in version 2 were initially introduced to atom size amid a plethora of other features. The presence of size in version 2 was not as pronounced as when students in version 1 observed it in the final two tasks. The variation between the two versions can be further explained by Deloache's reasoning for why students have a difficult time unpacking relevant information from more concrete representations (2001). Students in both versions must sort through multiple explicit features to identify the ones relevant to the task. Features that are more pronounced in comparison to previous representations leave students with the impression that they are essential to the sense making process.

Space Filling

The image of the space filling model was the last representation students worked with in version 1 and the initial representation students observed in version 2. Variation between student approaches in both versions were pronounced as students in version 1 identified features present in the previous tasks' representations, and students in version 2 did not have previous representations to consider in their approach to the task.

While only Sandeep strictly used atom size in version 1, several others attempted to reason with it, including Sarah who claimed that it was relevant to electronegatively exclusively in the space filling representation. Sarah's claim exemplifies the impact that these newly explicit features can have on student approaches. Conversely, Spencer's recognition that atom size was not relevant to the task, despite being a prominent feature, demonstrated a sub-facet of representational competence where the relevance of a feature to a chemical concept is assessed. Predominately, however, the way dipole-dipole interactions were determined seemed subjective in relation to the features present within the representation. This phenomenon reigned true for the participants that utilized the open site or octet approach in version 1. As the bond order was no longer explicit within the space filling representation, students considered the space around each atom as the location where dipole-dipole interactions could occur.

Similar to what was observed in the ball and stick task, size was not a factor students in version 2 considered when observing the space-filling representation. The array of explicit features present in the initial task for version 2 led students to approaches not observed in version 1 or any of the remaining representations in version 2. Four out of eight students utilized valence charge, citing the charges of the ionic forms of the atoms within the molecule retain. While several students connected this approach to electronegativity values, it is unclear what feature in the representation specifically cued students to this idea, especially considering the approaches' disappearance upon transitioning to the image of the ball and stick model. One explanation could be the representation itself. Parallel to the ball and stick representation, the concrete nature of the space filling representation makes it difficult for students to locate relevant features amid the number of explicit features inherent in the representation. In addition, the space-filling representation is not commonly used within chemistry instruction, except for rare instances when it is used within animations or demonstrations. Participants may be harkening back to when they observed the space-filling representation within the classroom and recalling a concept they learned in conjunction with this type of representation.

Intermolecular Force Conceptions

Through the exploration of representational impact on students' unpacking approaches, several findings were uncovered pertaining to students' conceptions of intermolecular forces. Participants in

this study brought forth several distinct ideas in how the location of dipole-dipole interactions could be identified. While many of the students employed a more canonical approach through the use of electronegativity values, others seemed to carry a conception that these interactions could be thought of in a similar fashion to covalent bonding. Participants identified sites where lone pairs resided on representations as unstable and in need of bonding. Rather than describing the dipole-dipole interaction in terms of an intermolecular force, students elected an approach where dipole-dipole interactions involved the formation of a new bond. Similarly, when lone pairs were not visible in a representation (space filling), several participants fell under the impression that a bond would be needed to fulfill the atom's octet. In addition, some identified the dipole-dipole interaction within the covalent bonds rather than between the molecules, matching prior observations in the research literature (Henderleiter, 2001; Cooper et al. 2013). When considering the verbiage used to delineate intermolecular and intramolecular forces, it is unsurprising that students conflate the two concepts. Bond is a word used when referring to different kinds of intermolecular forces and intramolecular forces. It is also important to consider the amount of time instructors dedicate to emphasizing intramolecular forces in comparison to intermolecular forces. Within general chemistry, intramolecular forces are covered and applied throughout the course content, while intermolecular forces are often isolated to their own chapter. Researchers became aware of this upon analyzing several general chemistry textbooks, finding the number of questions pertaining to intramolecular forces far outnumbered those dealing with intermolecular forces (Pappa and Tsaparlis, 2011). Considering that instructors tend to structure their classes around the content of the textbook (Bergqvist and Chang, 2017), it becomes clear why students might place more emphasis on covalent bonding, even when asked to identify intermolecular forces. In the context of this study, representational features appeared to be the deciding factor as to whether students conflated intermolecular forces and intramolecular forces. Representations with explicit features closely related to concepts students learn when covering covalent bonding (i.e. dots for lone pairs, lines for chemical bonds), drew students away from identifying molecular interactions and more toward models of chemical bonding.

Implications

This work was meant to build foundational knowledge, but some of the findings suggest areas that may improve instruction and are worth instructional consideration and evaluation. As teachers consider the utility of representations in their coursework, it is important to note how students are unpacking the representations and working with features. The results from this study call attention to the impact that altering representations can have on the way in which students understand chemical concepts and how they approach chemistry tasks. During the unpacking process of the various representations, students tended to emphasize the novel features specific to each representation. Some even carried over representational features that were present in one representation, but not applicable to others. These findings display many of the miscommunications that instruction may unknowingly communicate to students when utilizing various types of representations. To prevent this from occurring in the chemistry classroom at large, instructors may consider providing students with a foundation on how to work with and unpack relevant information from various types of representations. If an instructor plans on working with a particular representation, it will be likely beneficial to teach students the features that are externally represented and those internal features that must be deduced. A scaffolding technique may be of use in which students are first introduced to a representation using graphic organizers that allow them to identify the features present and absent from a representation. An example of an item in a graphic organizer is shown in Figure 9, where students would be prompted to classify select features as present or absent in the representation. The organizer would continue with additional representations.

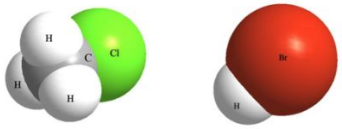
Representation	Categorize each feature below as present or absent in the given representation
Space Filling 	Atomic Size Bond Order Molecular Geometry Lone Pairs

Figure 9 Proposed intervention for teaching students how to navigate new representations

Additionally, in this study participants' interpretation of representations in each task was dependent on their interpretations of representations from previous tasks. With this in mind, instructors are encouraged to take time to contrast previously used representations and how they have been utilized when introducing new representations. This intervention's aim would be to emphasize that explicit features differ between representations and communicate the features present in one representation and absent in another. The students can then be given a chemistry task that utilizes the novel representation. Prior to solving the task at hand, students can be asked to write the features in the representation that are relevant to the task.

Nevertheless, the practice of chemistry is more than just the ability to decipher representations. Representations are used to simplify systems to understand the reasons behind phenomena (Stowe and Esselman, 2023). Therefore, the end goal is for students to know when to use representations that provide relevant information to the task (Gouvea and Passmore, 2017). As students become more used to working with various types of representations and their features, students can begin to use representations to deduce and justify their answers, an indication of a high level of representational competence (Kozma and Russell, 2005). For example, within the context of this study, a student might justify their answers using electrostatic potential maps to display the various electron densities present throughout each molecule. Lastly, in light of the representational influence on student understanding of intermolecular forces, it would be beneficial to investigate how ordering representations within instruction can be used to reinforce foundational intermolecular force concepts. While traditionally, instruction goes from abstract to concrete representations within the general chemistry classroom, it is of interest to uncover whether there are any benefits to reversing this ordering.

Limitations

It is important to note the qualitative nature of this study and that the results from this study cannot be generalized across all General Chemistry classrooms. Therefore, this study should be treated as exploratory work that seeks to uncover the way in which different representations impact a small set of students' approaches to unpacking representations and determining dipole-dipole interactions. One possible limitation that may have hindered this study's purpose was the inclusion of electronegativity values within the prompts. Initially, these values were provided to ensure students did not use up a large portion of the interview trying to locate the electronegativity values of the atoms in the periodic table. Upon reflection, the inclusion of these values may have influenced the number of times students utilized electronegativity in their approaches. Participants in this study often reverted to simply using the electronegativity values when they were unsure about how to unpack a representation. Several students expressed that the electronegativity values were provided for a reason and that they felt obligated to use them in some fashion. As a result, the full breadth of representational impact may have been stifled by the inclusion of the electronegativity values in the prompt. Another possible limitation that may have impacted the outcome of this study rested in the wording of the prompts. In the

prompts, students were asked to identify the pair(s) of atoms where the strongest dipole-dipole interaction would occur. Molecules with more than two atoms require that dipole moments between atoms be averaged to produce the overall molecular dipole. While this may have affected the way in which students answered each task, the influence of the representation would most likely remain. The possibility of positive selection in the recruiting process should also be considered. Students were enrolled in the study if they replied to the call for participants and showed interest in participating. Based on these selection parameters, it is possible these students may not fully represent the general chemistry student population.

Conclusion

Representations play a part in virtually every aspect of chemistry and are the foundation for understanding and applying complex chemical concepts. This study was able to identify several ways in which students' methods of unpacking could potentially be influenced by altering representations in a series of similar tasks. As participants undertook the representational unpacking process to find relevant information to approach the task at hand, many were cued by changes in the explicit representational features. The features depicted in the different representations caused students to utilize varying methods when attempting to determine the location of dipole-dipole interactions between molecules. These methods included the use of lone pairs as a bonding site, similar to what is observed in covalent bonding, citing bond strength, or invoking explicit features such as bond order and size. Additionally, the order in which students received the abstract/concrete representations influenced the specific features they took notice of and their approaches to the tasks. These findings contribute to the current literature on chemical representations and offer a new lens on how the way representations are presented impacts student conceptions of chemistry.

Conflicts of interest

Author S.E. Lewis receives funding from the Royal Society of Chemistry (RSC). The RSC had no active role in the data collection, data analysis, or interpretation of the data presented here.

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References

Becker N., Noyes K. and Cooper M., (2016), Characterizing students' mechanistic reasoning about London dispersion forces, *J. Chem. Educ*., **93**(10), 1713–1724.

Bergqvist A. and Chang Rundgren S.N., (2017), The influence of textbooks on teachers' knowledge of chemical bonding representations relative to students' difficulties understanding, *Res. Sci. Technol. Educ.*, **35**(2), 215–237.

Bodner G. M. and Domin, D. S., (2000), Mental models: The role of representations in problem solving in Chemistry, *University Chemistry Education,* **4** (1), 24-30.

Chittleborough G. and Treagust D. F., (2007), The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level, *Chem. Educ. Res. Pract*., **8**, 274-292.

Coll R. K. and Treagust D. F., (2003) Investigation of secondary school, undergraduate, and graduate learners' mental models of ionic bonding, *J. Res. Sci. Teach.,* **4** (5)*,* 464–486.

Cook M. Wiebe E. N. and Carter G., (2008), The influence of prior knowledge on viewing and interpreting graphics with macroscopic and molecular representations, *Sci. Educ.,* **92** (5), 848–867.

Cooper M. M., Corley L. M. and Underwood S. M., (2013), An investigation of college chemistry students' understanding of structure–property relationships, *J. Res. Sci. Teach*, **50** (6), 699–721.

Cooper M. M., Grove, N., Underwood S. M. and Klymkowsky M. W., (2010), Lost in Lewis structures: An investigation of student difficulties in developing representational competence, *J. Chem. Educ*., **87** (8), 869–874.

Cooper M. M., Williams L. C. and Underwood S. M., (2015), Student understanding of intermolecular forces: A multimodal study, *J. Chem. Educ*. **92**, 1288-1298.

DeLoache J. S., (2000), Dual representation and young children's use of scale models. *Child Dev.*, **71** (2), 329–338.

Domin D. S., Al-Masum M. and Mensah Z. J., (2008), Students' categorizations of organic compounds, *Chem. Educ. Res. Pract.*, **9** (2), 114–121.

Edelsbrunner P. A., Malone S., Hofer S. I., Küchemann S., Kuhn J., Schmid R., Altmeyer K., Brünken R. and Lichtenberger A., (2023), The relation of representational competence and conceptual knowledge in female and male undergraduates, *Int. J. STEM Educ.*, **10**, 1-19.

Farheen A. and Lewis S. E., (2021), The impact of representations of chemical bonding on students' predictions of chemical properties, *Chem. Educ. Res. Pract.*, **22** (4), 1035–1053.

Farheen A., Nguyen H. T., Nelsen I. and Lewis S. E., (2024), Students' approaches to determining the location of intermolecular force between two distinct molecules, *J. Chem. Educ*., DOI: 10.1021/acs.jchemed.2c01230.

Gkitzia V., Salta K. and Tzougraki C., (2020), Students' competence in translating between different types of chemical representations, *Chem. Educ. Res. Pract.*, **21**, 307-330.

Gouvea J. and Passmore C., (2017), 'Models of' versus 'models for': Toward an agent-based conception of modeling in the science classroom, *Sci. Educ.*, **26**(7), 49–63.

Gurung E., Jacob R., Bunch Z., Thompson B. and Popova M., (2022), Evaluating the effectiveness of organic chemistry textbooks for promoting representational competence, *J. Chem. Educ*., **99**(5), 2044–2054.

Hand B. and Choi A., (2010), Examining the impact of student use of multiple modal representations in constructing arguments in organic chemistry laboratory classes, *Res. Sci. Educ.,* **40** (1), 29–44.

Head J., Bucat R., Mocerino M. and Treagust D., (2005), Exploring students' abilities to use two different styles of structural representation in organic chemistry, *Can. J. Sci. Math. Technol. Educ.,* **5** (1), 133–152.

Henderleiter J., Smart, R., Anderson J. and Elian O., (2001), How do organic chemistry students understand and apply hydrogen bonding?, *J. Chem. Educ*., **78**(8), 1126.

Hoffmann R. and Laszlo P., (1991), Representation in chemistry, *Angewandte Chemie International Edition in English, **30*** (1), 1–16.

Hubber P., Tytler R. and Haslam F., (2010), Teaching and learning about force with a representational focus: Pedagogy and teacher change, *Res. Sci. Educ.*, **40**, 5-28.

Johnstone A. H., (1993), The development of chemistry teaching: A changing response to changing demand, *J. Chem. Educ*., **70**, 701.

Keig P. F. and Rubba P. A., (1993), Translation of representations of the structure of matter and Its relationship to reasoning, gender, spatial reasoning, and specific prior knowledge, *J. Res. Sci. Teach*., **30** (8), 883–903.

Keiner L. and Graulich N., (2021), Beyond the beaker: Students' use of a scaffold to connect observations with the particle level in the organic chemistry laboratory, *Chem. Educ. Res. Pract.*, **22**, 146-163.

Kozma R.B., (2003), The material features of multiple representations and their cognitive and social affordances for science understanding, *Learn. Instr.,* **13** (2), 205–226.

Kozma R. B. and Russell J., (1997), Multimedia and understanding: expert and novice responses to different representations of chemical phenomenon, *J. Res. Sci. Teach.,* **34** (9), 949–968.

Kozma R. B., and Russell J., (2005), Students becoming chemists: Developing representational competence, in Gilbert J.K. (ed.) *Visualization in Science Education,* Dordrecht: Springer.

Mayer R. E., (2011), Applying the science of learning to multimedia instruction, *Psychology of Learning and Motivation,* 77–108.

Pappa E. T. and Tsaparlis, G., (2011), Evaluation of questions in general chemistry textbooks according to the form of the questions and the question-answer relationship (QAR): The case of intra- and intermolecular chemical bonding, *Chem. Educ. Res. Pract.*, **12**(2), 262–270.

Patron E., Linder C. and Wikman S., (2021), Qualitatively different ways of unpacking visual representations when teaching intermolecular forces in upper secondary school, *Sci. Educ.*, **105** (6), 1173–1201.

Peirce C. S. and Buchler J., (1902), Logic as semiotic: The theory of signs, *Philosophical Writings of Peirce (New York: Dover Publications, 1955)*, 100.

Peterson R. F., Treagust D. F. and Garnett P., (1989). Development and application of a diagnostic instrument to evaluate grade-11 and -12 students' concepts of covalent bonding and structure following a course of instruction, *J. Res. Sci. Teach*., **26**(4), 301–314.

Pham L. and Tytler R., (2022), The Semiotic Function of a Bridging Representation to Support Students' Meaning-Making in Solution Chemistry, *Res. Sci. Educ.*, 1-17.

Rau M. A., (2017), Conditions for the effectiveness of multiple visual representations in enhancing STEM learning, *Educ. Psychol. Rev.*, **29** (4), 717–761.

Sandi-Urena S., Loría-Cambronero G. and Jinesta-Chaves D., (2019), Conceptualization of Lewis structures by chemistry majors, *Chem. Teach. Int.*, **2**(1), 791-849.

Scheid J., Müller A., Hettmannsperger R. and Schnotz W., (2018), Representational competence in science education: From theory to assessment, *Towards a framework for representational competence in science education*, 263-277.

Schmidt H.-J., Kaufmann B. and Treagust D. F., (2009), Students' understanding of boiling points and intermolecular forces, *Chem. Educ. Res. Pract.*, **10(**4), 265–272.

Schönborn K. J. and Bögeholz S., (2009), Knowledge transfer in biology and translation across external representations: Experts' views and challenges for learning, *Int. J. Sci. Math. Educ.,* **7** (5), 931–955.

Sim J. H. and Daniel E. G., (2014), Representational competence in chemistry: A comparison between students with different levels of understanding of basic chemical concepts and chemical representations, *Cogent Educ.*, **1** (1), 991180.

Stieff M. and DeSutter D., (2021), Sketching, not representational competence, predicts improved science learning, *J. Res. Sci. Teach*., **58**, 128-156.

Stowe R. L. and Esselman, B. J., (2023), The picture Is not the point: Toward using representations as models for making sense of phenomena. *J. Chem. Educ.,* **100** (1), 15–21.

Susac A., Planinic M., Bubic A., Jelicic K. and Palmovic M., (2023), Effect of representation format on conceptual question performance and eye-tracking measures, *Phys. Rev. Phys. Educ. Res.,* **19** (2), 020114

Taber K. S., (2013), Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education, *Chem. Educ. Res. Pract.,* **14**, 156-168.

Talanquer V., (2022), The complexity of reasoning about and with chemical representations, *JACS Au,* **2** (12), 2658–2669.

Treagust D., Chittleborough G. and Mamiala T., (2003), The role of submicroscopic and symbolic representations in chemical explanations, *Int. J. Sci. Educ.*, **25**, 1353-1368.

Widarti H. R., (2021) Multiple representations in chemistry learning: A study on teachers' literacy, in Suwono H., Habiddin H. and Rodic D. (ed) *The 4th International Conference on Mathematics and Sceince Education (ICoMSE) 2020: Innovative Research in Science and Mathematics Education in The Disruptive Era,* **2330***,* 020042.

Wu S. P. and Rau M. A., (2018), Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations, *Learn. Instr.,* **55**, 93-104.

Xu L., (2021), Towards a social semiotic interpretation of the chemistry triangle: Student exploration of changes of state in an Australian secondary science classroom, *Int. J. Sci. Math. Educ.*, **20**, 705-726.