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# Representational Technologies and Learner Problem-Solving Strategies in Chemistry

## ABSTRACT

Learning within the sciences is often considered through a quantitative lens, but acquiring proficiency with the symbolic representations in chemistry is arguably more akin to language learning. Representational competencies are central to successful communication of chemical information including molecular composition, structure, and properties. This article reports on a qualitative study of learner experiences when introduced to new symbolic representations and representational technologies. Participants' descriptions of these resource interactions were collected through semi-structured interviews and surveys, and were analyzed using phenomenography to identify the variety in student experiences. Results illustrate the impact that representational technologies can have on learner development of problem-solving techniques.

## KEYWORDS

chemistry, language development, phenomenography, problem solving, technology

## INTRODUCTION

The symbolic language of molecular representations is central to communication between chemists and is vital to the thinking processes of an individual chemist. Molecules are too small for all but the most sophisticated instruments to resolve, and thus symbolic molecular representations must convey information about atomic connectivity, molecular shape, and electronic distributions. These properties, in turn, are used to predict others such as physical state and reactivity. General Chemistry courses at the college or university-level typically include an introduction to numerous chemical notations and representations. As Habraken (2004) explains,

> *Chemists cannot talk to each other without the use of drawings and, increasingly so, by using computer-generated pictures and molecular models. Because, in chemistry, the picture has become more than this; it has become a way of thinking and the dominant way of thinking…. The evolution from the first primitive drawings of 125 years ago to today's computer-generated drawings is a clear demonstration of the simultaneous evolution of a science and its scientific language.* (pp. 90-91)

Each type of molecular representation was created to convey particular information or construct a novel way of thinking. Consequently, each generation of new representations has often preceded major developments within the field (Goodwin, 2008). For learners to successfully use molecular representations, they need to develop representational competence, a set of skills for interpreting,

transforming, coordinating, and constructing external representations used when learning or problem solving within a specific domain. Consider the work of Kozma and Russell (1997), in which chemical novices were differentiated from experts through their efficacy at transforming and coordinating between multiple representations of chemical phenomena. Additionally, the ability to rotate objects mentally has been linked to career path (Wai, Lubinski, & Benbow, 2009). However, this may be more of a reflection of expectations during career training than professional expertise required in the field: "as domain-specific knowledge increases, the need for the abilities measured by typical spatial abilities tests goes down" (Uttal & Cohen, 2012, p. 152). As Uttal and Cohen note, "The reason spatial abilities matter early on [in STEM fields] is because they serve as a barrier; students who cannot think well spatially will have more trouble getting through the early, challenging courses that lead to dropout" (p. 177).

McCollum, Regier, Leong, Simpson and Sterner (2014) discovered that learners with a distribution of spatial ability were better able to complete representational transformational challenges with the aid of touch-screen tablet technology than using traditional means. Rather than provide spatial training to help students overcome the barrier of spatial reasoning, the iPad removed this barrier. This aligns with the work of Sweller (2008) and Mayer (2005) on cognitive load theory, showing that technology can alleviate the cognitive load for novices while they engage with new concepts. Learners were still required to interpret each chemical representation and correctly transform from one representational mode into another, meaning that the disciplinary knowledge remained intact in the learning exercise. We propose that the objective of chemistry education is not to perform mental rotation of symbolic representations but rather to draw chemically meaningful conclusions from these representations. Therefore, it can be argued that the tablet experience led to disciplinary learning. McCollum et al. (2014) observed that, even after the iPad was put away, these same learners demonstrated increased representational construction skills. As novel representational modes, such as the iPad, are introduced into chemical education, it is valuable to assess how learners use these tools when transforming between representations and the relative value that learners ascribe to these modes.

In this paper we will present how learners confronted with unfamiliar content will interact with various representational technologies. We will show that the iPad, a technology preferred by less than half of the participants, supported the development of higher-level problem-solving skills for interpreting and transforming symbolic representations of 3D systems as compared to the other options. In particular, we will present results that support the hypothesis that learners use the iPad to bridge between 2D and 3D representations.

## INTRODUCING NEW EDUCATIONAL TECHNOLOGIES FOR REPRESENTATION OF MOLECULAR SHAPE INTO GENERAL CHEMISTRY

In this study, technology is defined as a machine, piece of equipment, method, notation, or visual representation that is created through scientific endeavors to solve problems or communicate information. Thus, our definition includes technologies traditionally used to teach molecular shapes and geometry. Static printed images as found in textbooks are commonly used in General Chemistry to represent molecules. When teaching molecular shapes it is standard to use plastic models in conjunction with static images. More recently, computers and computer-based images have also been integrated into chemical education, typically as instructor demonstrations. These have been shown to provide advantages such as improved question posing, inquiry and modeling skills, and representational competence skills (Kaberman & Dori, 2009; Stieff, Hegarty, & Deslongchamps, 2011; Stieff, Ryu,

Dixon, & Hegarty, 2012). Little is known about the student experience when manipulating structures using the iPad.

New technologies for chemical education are often assessed through quantitative analysis of learner performance on tasks, either through the use of pre- and post-tests and/or using control and experimental groups (Kaberman & Dori, 2009; Stieff et al., 2011; McCollum et al., 2014). Mixed method approaches involving quantitative analysis of interviews and survey tools are also found (Moore, Herzog, & Perkins, 2013). Presently, we aim to examine representational technologies in chemistry using a qualitative approach to identifying the variations in the student learning experience when using educational technologies for representation of molecular shapes. Such information can inform the development of best practices for employing educational technologies. This is of particular importance with the expanding use of touch-screen technology, such as the iPad, in visualization-based science education (McCollum et al., 2014; Morsch & Lewis, 2015; Shelton & Jones, 2013; Torres Gil, 2011).

### Assessing problem-solving strategies

Cognitive and educational psychologists have proposed theories of problem solving (Jonassen, 2000; Sinnott, 1989). The exercises of transforming between chemical representations used in this study can be considered well-structured problems (Jonassen, 1997) because each meets the following criteria:

- presents all necessary elements to solve the problem;
- requires the application of a limited number of regular and well-structured rules that are organized in prescriptive manner;
- the relationship between decision choices and all problem states are known or probabilistic;
- possesses correct, convergent answers.

While there is no widely accepted system for organizing all possible problem-solving strategies, methods for assessing problem-solving strategies related to well-structured problems involve coding based on strategy type (Jonassen, 2014). We argue that, for some well-structured problems, it is possible to rank the strategies based on properties such as the accuracy, complexity, or efficiency of the process. In this study we will use accuracy (will the strategy lead to the right answer?) and complexity (based on the awareness of the system demonstrated through the strategy) to rank the problem-solving strategies that students employ to interpret and transform symbolic represents.

PHENOMENOGRAPHY

The theoretical framework used in this study was phenomenography (Marton, 1981). This should not be confused with phenomenology (Moran, 2000). While both frameworks focus on human experience as the object of study, phenomenology is used to understand the *meaning* of a chosen experience or phenomenon. Phenomenography, in contrast, is used to identify the variations in how people experience the phenomenon.

Phenomenography serves well for inductive hypothesis-generating research, as opposed to hypothesis-testing research (Glaser & Strauss, 1967). This established research methodology studies "the limited number of quantitatively different ways in which various phenomena in, and aspects of, the world around us are experienced, conceptualized, understood, perceived, and apprehended" (Marton, 1994). Thus, while people may experience a given phenomenon in categorically different ways, this framework presumes that the possible variations are finite; using a sufficiently large sampling, a researcher may observe the complete set of variations for a given population.

Phenomenography finds application in research that involves discovering connections or links between the phenomenon that is being studied and the research participants. Another view of phenomenography is that it helps the researcher identify the relationships that the participants themselves establish about the object (the phenomenon under investigation) (Pang, 2003). The phenomenon is not to be considered in the absence of the people that experience it (Bowden, 2000; Limberg, 2000). Rather, phenomenography permits the study of these conjoined subject-object relationships that are referred to as experiences (Yates, Partridge, & Bruce, 2012). For these reasons, phenomenography is most frequently employed when studying teaching and learning (Entwistle, 1997; Edwards, 2007). As Booth (2008) explains "phenomenographic research points to individual learning, but tackles it at a collective level, which is to say that the empirical results lie at a level above the individual but can inform the researcher and the teaching practitioner of the learning practices even at an individual level" (p.451).

As with any research tradition that relies upon human communication for data collection, there are inherent challenges in interpreting phenomenographic data. Saljo (1997) explores some of these issues: how people use a limited number of ways of talking about a phenomenon, and the potential relationship (or lack thereof) between participants' descriptions of the experience and the actual experience. "Phenomenographers observe, collect and analyse discourse, and when the results become interesting is when there is a discursive practice in which people are trying to achieve something" (p. 179).

The reliability and reproducibility of conclusions emerging from phenomenographic studies is addressed by Sandbergh (1997) with a proposed criterion of the researcher's interpretative awareness. The experiences of the researcher will influence the research process, from design of the research question through analysis of the data and formulation of conclusions. Thus, the researcher must address these unavoidable biases, and where possible implement controls or checks on his/her interpretations.

The outcome of any phenomenographic analysis is a set of well-defined and logically related categories that encompass, ideally, all variations in how participants experience and relate to the phenomenon being studied (MacMillan, 2014). This set emerges from the data once analysis starts rather than being predicted prior to data collection. An acceptable set should meet the following criteria for each member category in the set (Marton & Booth, 1997; Bruce, 1997):

i. the category must describe a distinctly different aspect of the experience (it must be qualitatively different from the other categories);
ii. the category should logically be related to each other category;
iii. when included with all other member categories, the category completes the set to describe the observed critical variation.

Such a set should contain as few members as is feasible and reasonable for capturing the critical variation in the data (Marton & Booth, 1997). It is important to note that the resulting set is dependent not only on the phenomenon but also on the population under study, or even on the sample of participants from the population. Therefore, the population must be well-defined when reporting a set of categorized experiences.

The observed set of categories is formally referred to as the outcome space (Andretta, 2007; Åkerlind, Bowden, & Green, 2005; Booth, 1997). Three possible types of outcome spaces, based on the structural relationships between the categories, are:

• an inclusive, hierarchical, outcome space;
• a developmental progression outcome space;

- an interviewee past-experience dependent outcome space. (Laurillard, 1993)

This study resulted in a developmental progression outcome space, meaning that categories for how a phenomenon is conceived can be ordered by their explanatory power.

## METHOD AND INSTITUTIONAL CONTEXT

The purpose of a phenomenographic study is to detect and describe the outcome space, the variety in experiences the population of interest has with the phenomenon under investigation. Clearly, some random samplings may not reveal the full outcome space of the phenomenon for the associated population. Thus, in some studies non-random selection of participants may occur (Åkerlind et al., 2005). Another option is to conduct interviews until saturation is reached, the point at which no additional critical variations in experience can be identified (Dunkin, 2000; Morse, 1994; Sandberg, 2000; Trigwell, 1994). This has the twofold benefit of the observed outcome space tending toward the true outcome space while also maintaining a manageable data set (Trigwell, 2000; Bowden, 2005).

The objective of the present study is to identify the variations in the student learning experience when using educational technologies for representation of molecular shapes. Ideally, the outcome space resulting from this study will be informative to educators at many institutions, yet it is important to note that the target population and all sampling occurred at a large undergraduate-only university in Western Canada and hence the outcome space will reflect such.

Participants were recruited from the course sections of first semester university-level General Chemistry. At our university this course follows the "atoms first" approach, which initially focuses on the connections between the submicroscopic and macroscopic levels of matter rather than the arithmetic of macroscopic behaviour. The majority of our students is taking the course for their first time and have minimal experience with molecular shape. Thus, to have an outcome space that represents the variety of experiences a new learner may have, we restricted sampling to students who were taking the course for their first time.

Usually, a phenomenographic study involves interviews with the participants (Yates et al., 2012). These interviews focus on the subject-object relationship, often using the subjects' own descriptions of their experiences, as they interpret them, to define those experiences. In order to achieve this goal, the interview process must be adaptable within reason to properly explore the possible variations in the subject-object relationship.

Volunteers ($n = 20$) underwent a 90-minute semi-structured individual interview that was conducted by a member of the research team, but not the course instructor. Sampling continued until the saturation point was reached, and all interviews were completed before the topic of molecular geometry, valence-shell electron-pair repulsion (VSEPR) Theory was introduced in the course (Gillespie, 1963). Prior to the interview, participants were assessed on their pre-existing visual-spatial ability using sixteen Shepard and Metzler type mental rotation test items (Peters & Battista, 2008).

The five stages of the interview are outlined in Figure 1. Details on the interview process are provided in the Appendix. Before the interview proper began, the participant was asked to voice aloud all of their thoughts throughout the interview. If at any time the participant became quiet, they were prompted to describe their experience.

The same eleven geometries were presented for each mode in black and white to maintain learner focus on the representation type, rather than on the atomic coloring conventions used in chemistry. Examples are provided in Figure 2. Participants were introduced to structural formulae using the example molecule shown in Figure 3. Recall that the participants had minimal-to-no prior experience

with these representations, yet by Stage 2 of the interview many participants had become sufficiently familiar with the geometries that they were naming the shapes before the interviewer.

**Figure 1. The five stages of the interview protocol. Participants were asked to "think aloud" throughout the interview.**
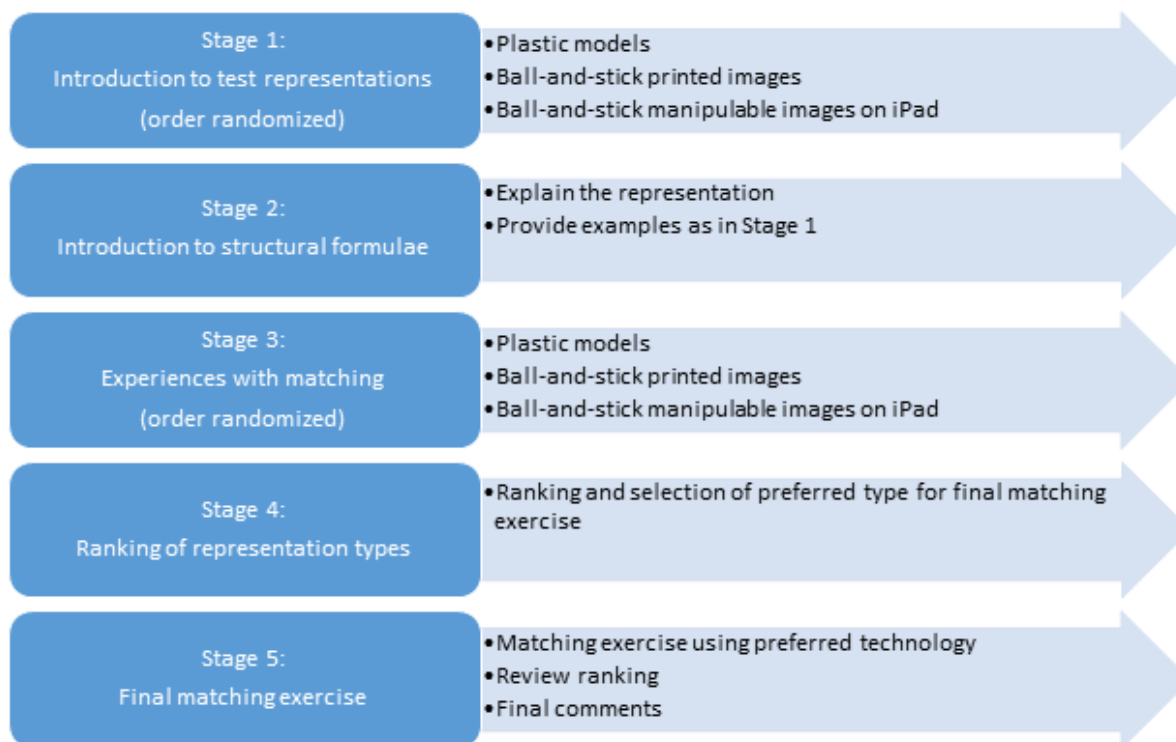


| Stage 1: Introduction to test representations (order randomized) | • Plastic models<br>• Ball-and-stick printed images<br>• Ball-and-stick manipulable images on iPad |
| Stage 2: Introduction to structural formulae | • Explain the representation<br>• Provide examples as in Stage 1 |
| Stage 3: Experiences with matching (order randomized) | • Plastic models<br>• Ball-and-stick printed images<br>• Ball-and-stick manipulable images on iPad |
| Stage 4: Ranking of representation types | • Ranking and selection of preferred type for final matching exercise |
| Stage 5: Final matching exercise | • Matching exercise using preferred technology<br>• Review ranking<br>• Final comments |

**Figure 2. Tetrahedral molecular geometry**



(a)   (b)   (c)

The tetrahedral molecular geometry as represented in the modes of (a) plastic model; (b) static ball-and-stick printed image; (c) structural formula. The arbitrary symbols A and X have been used in the structural formula representation to represent the central and surrounding atoms. This convention was maintained for each of the eleven example structural formulas presented in Stage 2. The manipulable ball-and-stick image on iPad (not shown) would look the same as the printed image when left in a static position. The key difference was that the participant could rotate the manipulable image in virtual 3D space with direct tactile interaction on the iPad screen.

**Figure 3. The structural formula for estrogen.**



This structure was used to explain to participants how wedges (thick lines illustrating bonds coming out of the plane of the paper), hatches (dashed lines illustrating bonds going behind the plane of the paper), regular lines (illustrating bonds that are in the plane of the paper), and double bonds are interpreted in this type of molecular representation. Implicit atoms (unlabelled atoms or groups of atoms at vertices or at the end of a line) are also present in this structure to reduce complexity, but were not used in the simpler representations used during the matching exercises. As such, these were only discussed if a participant made an inquiry.

During the matching exercises (Stage 3) the learners were presented with a single representation from one of the three test representation types and asked to match it with the corresponding structural formula from a set of four options. The representations used in the exercise in Stage 3 involving the static image are provided in Figure 4. Representations for the other exercises can be found in the appendix. Our focus was on the learner's experience with the phenomenon, not on the accuracy of their response. Thus, if the participant's response was not correct, they were invited to make another attempt until they arrived at the correct match. We wanted the participant to explore and describe the experience without feeling the pressure of an assessment. After the participant ranked the three representation types in order of their preference (Stage 4), they then selected one of the representation modes for a final matching exercise (Stage 5) that was more challenging than the original three exercises.

**Figure 4. Molecular representations used in the static ball-and-stick (printed) matching exercise. The structural formula that matches the image is option D.**
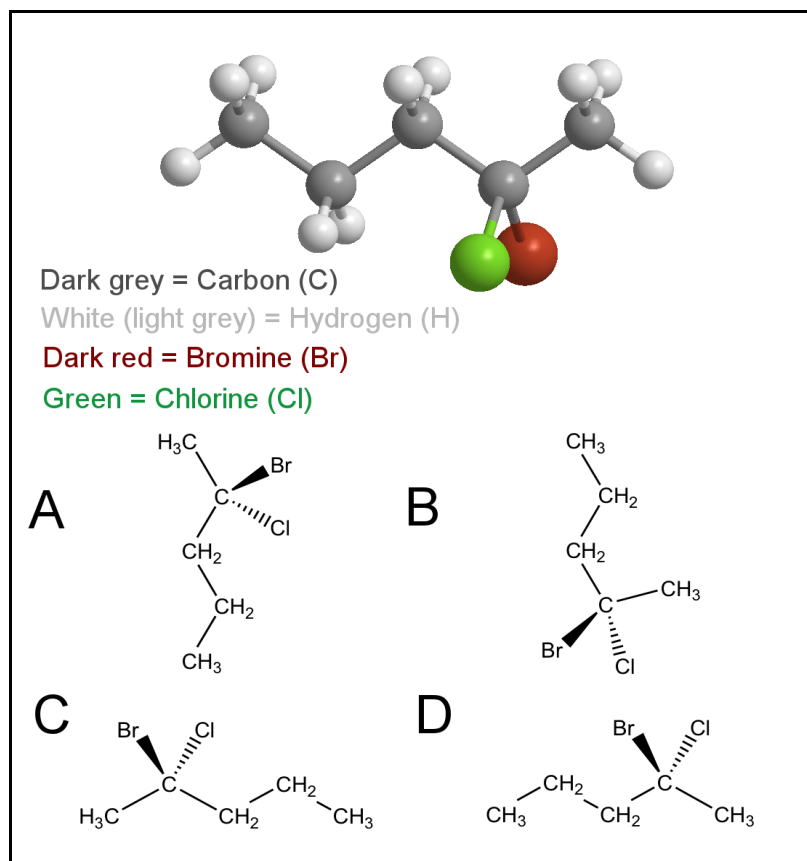


### Demographic data

Just over half (55%) of participants were female, which is normal for this course. Similarly, the age (mode: 18, mean: 20) and distribution of intended majors of our sample closely resemble those found within the course. All participants indicated that they own a mobile device. They responded to the question of "how much do you enjoy using a mobile device" with a numerical response of either 4 (like) or 5 (love) out of 5. All participants report using their mobile device daily. Informal classroom discussions indicate that over 90% of our students own a personal smartphone that they carry with them daily and over 50% have regular access to a mobile tablet.

Based on the sixteen Shepard and Metzler type mental rotation test items the sample of current participants was compared to participants in a previous study (McCollum et al., 2014) using a Mann-Whitney U-test, a nonparametric test that can be applied to unknown distributions (Mann & Whitney, 1947). With median scores in the previous and current study of 11 and 13.5 respectively, the two samples are considered to be from the same population (Mann-Whitney $U = 62$, $n_1 = 10$, $n_2 = 20$, $P = 0.10 > 0.05$ two-tailed), a 'typical' General Chemistry population at our university.

### Approach to data analysis

Phenomenography does not have a defined procedure or technique for data analysis. Strict adherence to one approach would be problematic due to the dynamic nature of phenomenography

(Yates et al., 2012). Interviews were transcribed, and clarifying information was added in brackets when appropriate based on the video recordings. This was followed by identification of all key passages for a given chemical representation. These were then isolated from the source (interview number) and reorganized based on categories that emerged from the passages.

Whereas we sought to better understand the learner experience with an assortment of chemical representational technologies (structural formulas, plastic models, printed ball-and-stick, manipulable ball-and-stick), our approach was to apply the phenomenographic tradition across our sample considering each type of representation separately at first. An iterative process was employed to generate and refine a coding system for each chemical representation under investigation. This iterative process involved analyses by all members of the research team, which included an experienced chemistry professor and two undergraduates enrolled in different BSc programs. The differences in backgrounds and experiences among the research team served as a control when interpreting participants' interviews, improving interpretative awareness (Sandbergh, 1997).

The emerging outcome spaces for the separate representations were found to significantly overlap, and thus the data for the different representation types was brought together to form a unified coding system that could be applied across the entire data set. This coding system was then used to code all transcripts. Additional revisions of the coding system followed, leading to a strong familiarization with the transcripts and final coding system.

The emergent outcome space revealed a complex multi-layered system. Not only did participants describe experiences when working with a particular representation that could be categorized according to the phenomenographic tradition, many of these categories reemerged with other representations but in distinctly different ways.

## REPRESENTATIONAL TRANSFORMATION EXERCISES USING CHEMISTRY EDUCATIONAL TECHNOLOGIES

We begin our analysis considering the learner experience when working with plastic models and structural formulae, and will then compare the other options to that outcome space.

### Transforming from a plastic model to a structural formula

For the phenomenon of transforming from a plastic model to a structural formula, participants used three main strategies: (A) sequential tracking; (B) isolation and branching; and (C) spatial orientation. Comments that match category (A) focused on the sequential order of connected atoms in the molecule as they simultaneously tracked corresponding atoms in both representations:

> So the first [option] has 3 C's and then the end is connected to 2 H's one O and one H. So that seems pretty right. (Interview 4)

Keep in mind that all of the structures used in the assessments were chiral; switching the bonding positions of two groups at the chiral center would create a different molecule that is a mirror image of the original but may behave differently in a chemical reaction. Structural formulae options C and D in Figure 4 are mirror images of one another with the –Br and –Cl groups switching positions (forward and back). This topic is typically not taught until 2nd year organic chemistry. Participants eventually found that sequential tracking was an ineffective problem-solving method. It is impossible to differentiate between the structural formulae using this approach as all four options consisted of the

same elemental composition and atomic connectivity, differing only in the 3D spatial arrangement of the atoms. Additionally, the complexity of this strategy was very low, focusing only on the connectivity within the molecule from a potentially inconsequential starting point. For this reason, this strategy is ranked lowest in the outcome space.

Evidence that fits within category (B) illustrates the use of a reference point on the plastic model as a means of transforming from one representation to the other. Participants describe their experience as consisting of first isolating or fixating on one component of the structure, such as the carbon skeleton, a particular colored atom, or groups of atoms, to help familiarize themselves with the model. The rest of the molecule was then examined by branching out from their selected reference point. Participant 17 began by concentrating on the carbon with the hydroxyl group (-OH), explicitly calling it their point of reference:

> *Well first I'm going to start with the simpler side, because this is a carbon with oxygen [and] hydrogen, so I have to find something that corresponds with this, a point of reference, and checking cues that match. (Interview 17)*

Similar to the sequential technique, the learner would eventually find that all structural formulae had the same groups branching out from any reference point, and a different approach that takes into consideration spatial arrangement, was required. While this technique was also futile, it involved identification of a key portion of the molecule and examination of the attached groups. Based on this higher level of complexity, the isolation and branching technique has been ranked above sequential ordering.

The third category of experience, category (C), is spatial orientation. Similar to the isolation and branching approach, participants described focusing on a portion of the molecule they felt was key to the solution but then considered the relative orientation of the groups in both representations at that point, rather than simply exploring the connectivity that branches out from it. Generally, it was only after a participant described using this approach that they were successful at establishing the correct match. Participant 9, while focusing on the hydroxyl group compared the plastic model's spatial positions of the -OH and the -H on the same carbon with the depictions of the same groups' spatial positions in the structural formulae:

> *I don't think it's this one because I think the H kind of comes out. I can see the OH here and then the wedges don't really match to me. (Interview 9)*

At this point they had not yet arrived at the solution, but they did identify the necessary approach. Participant 6 used the same technique, but was clearer in their description. They explained their approach as attempting to match the plastic model to each structural formula in turn through physical manipulation:

> *I'm looking mostly at the lines that are representing going into the page and the ones coming towards me, so I am just trying to get it [the plastic model] like that. [Physically manipulates model]. Okay! (Interview 6)*

Interview video recordings revealed that both participants visually focused on the hatches and wedges of the structural formulae while manipulating the plastic model. Once they found that this approach would

allow them to discard some of the options, they maintained their concentration on the key portion of the molecule. This strategy meets the primary goal: it allows the learner to solve the problem. As the only effective strategy, we rank spatial orientation as the highest level problem-solving strategy in this outcome space.

During the exercise of matching a plastic model to a structural formula, the experience of an individual participant was usually not restricted to only one category. Descriptions of the phenomenon revealed the process learners would move through in their problem-solving strategy development. The outcome space for this particular phenomenon resembled a developmental progression as illustrated in Figure 5.

**Figure 5. The outcome space of problem-solving strategies that learners described and developed as they experienced transforming between the representational technologies of plastic models and structural formulae.**



Sequential Tracking    Isolation and Branching    Spatial Orientation
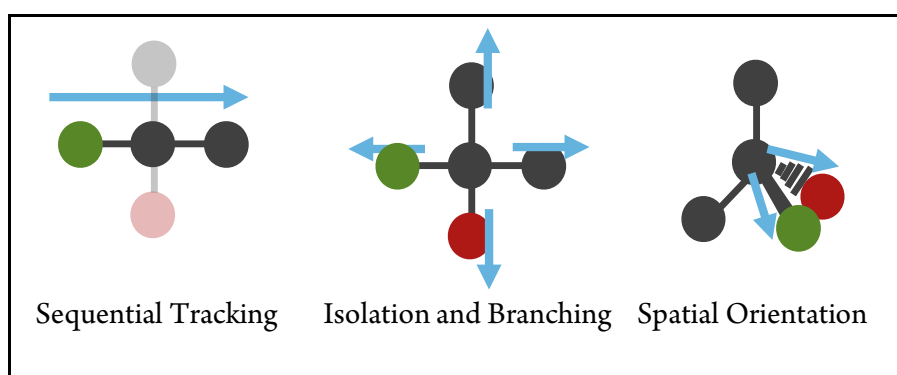
Some learners progressed through all three categories in order, others skipped one or both of the lower levels of strategy, but none moved backwards during the matching exercise using the plastic model. Almost all learners eventually discovered the spatial orientation technique when using the plastic models, supporting the continued use of this representation mode.

### Transforming from a manipulable ball-and-stick image on iPad to a structural formula

We observed the same outcome space during the exercise in Stage 3 of matching a manipulable image on iPad to a structural formula. This was true regardless of whether the plastic model matching exercise came before, after, or between the static image (paper) and manipulable image (iPad) exercises. However, the frequency at which each category was observed did vary. When students moved from a manipulable ball-and-stick image on the iPad to the corresponding structural formula, based on the number of comments that fit each category, there were significantly fewer uses of the sequential tracking technique and correspondingly more experiences that matched the spatial orientation category. Additionally, participants were discovering (or rediscovering) the spatial orientation technique sooner when using the iPad.

Several participants noted that the iPad image could appear like a 3D object when moving, or a 2D image when left in a position, and compared this strength with the plastic model or static paper image:

*I like the iPad because I can freely rotate it around. And since this [plastic model] is real life … it doesn't have that 2D that I need to actually solve one of these [questions] since this [structural formula] is the 2D version. (Interview 16)*

Here Participant 16 identified a challenge with the plastic model—they could not collapse the 3D model onto a 2D representation. They preferred the iPad because it can be manipulated in a virtual 3D environment (unlike the static paper image) and it can also be set to a fixed orientation, at which point it is simply an image on a 2D surface (unlike the plastic model) and thus easier to compare with the structural formulae. While this relationship has been hypothesized before (McCollum et al., 2014), this is the first report of learners describing the iPad as helping them bridge between 2D and 3D representations.

### Transforming from a static ball-and-stick image to a structural formula

In contrast to the other phenomena, when working with the static ball-and-stick printed image there was a dramatic shift in the distribution of comments toward the simpler and unsuccessful sequential tracking technique. Interestingly, this shift was observed even if the paper exercise came after the other two technologies. Participants did not know how to apply the more successful spatial orientation technique to the static image.

Consider the example of Participant 20 working on the static paper-based image exercise:

*So I'm looking at the first one, $CH_3$. Then the next one is $CH_2$ and it seems like all of them [the options] have the same thing. $CH_2$ next one, they all have the same. They're all the same! (Interview 20)*

This individual had already experienced the iPad exercise and learned to focus on the spatial orientation of the groups, but when using the static paper image they reverted to the sequential tracking technique and seemed to carry forward none of the spatial awareness they had demonstrated in the earlier exercise.

## DISCUSSION

Two significant results emerge. First, while each of the three phenomena had a developmental progression outcome space, this development did not necessarily carry over into subsequent phenomena. Familiarity with a type of problem is known to impact problem-solving success, and representation of a problem in another way usually restricts transfer of the problem solving skill (Gick & Holyoak, 1980, 1983). Even if the learners had discovered the spatial orientation problem-solving technique during one exercise, they didn't immediately reuse the technique in the next exercise. Although the learners were not told that all three exercises involved the same type of problem (using different modes of representation), we expected they would attempt to reuse a successful approach. Instead, the learners associated the problem-solving approach with the technology, not with the type of problem. This forced them to struggle and rediscover the correct approach multiple times.

Secondly, the data suggests that the type of representational technology an instructor chooses to use with his or her students can have a direct impact on the problem-solving strategies the learners develop. The frequency with which each category was observed varied with the type of representational technology used. Based on our sampling, the manipulable images on the iPad were the best choice for

promoting spatial awareness, followed by the plastic model. The static images were the least effective in this independent exploratory-learning environment.

While the plastic model is a better representational technology than the static images, learners expressed having difficulty interpreting how the plastic model is meant to relate to a structural formula:

> *I can't visualize it correctly to see this one right. Since there's so much lines, I can't visualize it. Can I just guess? (Interview 16)*

Many participants described having some experience working with plastic models in high school chemistry classes, but this did not seem to imply that they understood how to interpret the spatial information contained in the plastic model. Rather, they related their past experience to discussing atomic connectivity (order of the connected atoms).

Another issue with the plastic model was the additional degrees of freedom where participants could twist the bonds in the plastic model, changing the internal coordinates. In contrast, the 3D virtual images on the iPad rotated as a fixed molecular unit. Many students did not like the additional complexity afforded by the plastic model.

> *I can see it being detrimental or confusing that I can rotate [the bonds]. I don't know if that's a good thing or a bad thing that I'm able to do that, but I could see myself getting all mixed up by being able to do that. (Interview 11)*

Participant 11 poses an important question: is the additional complexity of the plastic model a good or bad thing? In an advanced chemistry course where bond rotation and steric hindrance are discussed, clearly this feature of the plastic model is advantageous. Yet, for General Chemistry students, we observed this level of complexity leading to cognitive overload.

The iPad appears to have reduced cognitive load in two important ways. It served as a digital manipulable through direct tactile interaction, relieving participants of the mental rotation task so they could instead focus on representational transformation. The iPad also restricted rotation to the entire molecular unit, not individual bonds, reducing the complexity of the representation. Despite its benefits, only 40% of participants chose this technology for the final matching exercise. More participants (50%) chose the plastic model and two (10%) chose the static paper-based image. This may be surprising, considering all participants indicated they like or love their personal mobile device, and that they used it daily. However, many participants commented during the interviews about their lack of familiarity with the specific mobile app used for representing molecular structures. Consider how Participants 6 and 10 describe the impact of familiarity on their choice of preferred technology.

> *The iPad, I am just not used to moving things around like this, so I was having a hard time, like how it would rotate and trying to grab at different points to rotate it. (Interview 6)*

> *It's just the technology that I struggle finding the correct angle because it would be ranked right up there if I didn't struggle with that, which might just be practice even, learning to use the technology better. (Interview 10)*

In contrast, almost every participant discussed having experience in high school using plastic models. High self-efficacy students are known to use more effective learning strategies and self-

regulation practices (Schunk & Ertmer, 2000). Past experience with learning technologies appears to have a strong influence on learner self-regulation practices. Specifically, the majority of students chose a technology they were familiar with over the most effective resource. Thus, we argue that a student's self-efficacy is impacted by the introduction of learning technologies that are new to the user, including mobile apps. In our opinion, learners must be provided sufficient time and training to familiarize themselves with a learning resource before they will consider it an effective resource.

Static ball-and-stick images in textbooks are commonly used when teaching molecular structure, yet this was the least preferred mode. The two participants who selected static paper-based images as their preferred technology both explained their choice in terms of familiarity. They also stated that they already knew how to mentally manipulate objects and did not require a technological aid to manipulate representations. The opinions of these two participants align with a narrative often heard at conferences on chemistry education, that if students just learn how to conduct mental rotation, then manipulables (such as the plastic model and the iPad image) are unnecessary. Despite their confidence, these participants did not score higher than the sample average on the mental rotation pretest, which used static paper-based images. Recall also that these participants only represent 10% of the sample. If the target audience of a learning intervention is a General Chemistry class, then the needs and preferences of the other 90% of the learners should also be considered. After all, regardless of these arguments, we maintain that the objective of chemistry education is not to perform mental rotation of symbolic representations, but rather to draw chemically meaningful conclusions from these representations.

## CONCLUSIONS

Our results indicate that the iPad as a touch-screen tablet promoted development of higher-level problem-solving strategies by chemistry students for transforming between common chemical representations than the traditionally used representational technologies of plastic models and static ball-and-stick images. This was observed for students across a range of visualization abilities, as assessed with Shepard and Metzler mental rotation stimuli, enabling a wide range of learners to successfully complete representational transformation exercises.

Although the iPad enabled more participants to discover the spatial orientation technique, only 40% of participants chose the iPad as their preferred technology. More popular (50%) was the plastic model, demonstrating that participants were not simply attracted to the trendy gadget. Based on our observations, we argue that the level of familiarity a learner has with a specific learning resource will impact whether some learners choose to utilize the learning resource, regardless of its association with their chances of success. Greater familiarity with touch-screen tablets and improvements to the software may change this preference among a General Chemistry population.

As the learners described their experience using the iPad and plastic models, the words they chose revealed spatial thinking. They focused on the 3D distribution of the atoms and how rotation of an individual bond or the entire molecular unit would change the spatial positions relative to their vantage point. Thus, we propose that indirect spatial training is a side benefit of using these manipulables. Not only did the iPad remove the barrier of spatial thinking so that the learner could complete the representational transformation exercise, the technology was providing the learner with an opportunity to think spatially.

Learner progression through the three observed problem-solving strategies with any of the technologies was unidirectional, toward the more successful strategies. This indicates the value of experiential learning / guided inquiry activities with symbolic chemical representations. However,

learners did not appear to transmit the spatial understanding they gained with one technology to another. Therefore, we urge educators to judiciously reflect on the variety of representations used in their instructional approaches and assessments.

The observed higher-level problem-solving skills demonstrated that the participants both understood how to interpret the representations and were more capable of transforming between the chemical representations. With learner development of representational competencies being a goal within chemistry education, the use of technologies and tools that support such skill development is worthy of consideration.

When evaluating the benefits and challenges of adoption or abandonment of a molecular representational technology, it is imperative to consider the diversity of experiences learners have with that representational technology. Modern tablet technology, in addition to convenience, assists student learning. However, to simply say that one approach is better than another ignores the variety in learner familiarity with representational technologies. Endeavors to adopt a new representational technology should be responsive to this diversity in learner experiences, and include student training to increase familiarity with new resources.

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