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A Review of Spatial Ability Literature, Its Connection to Chemistry, and Implications for Instruction

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Consider Galton's closing remarks on *Mental Imagery (1)*:

> All that remains to be said refers to the utility of the visualizing faculty, and may be compressed into a few words. A visual image is the most perfect form of mental representation wherever the shape, position, and relations of objects in space are concerned.... The pleasure its use can afford is immense.... Our bookish and wordy education tends to repress this valuable gift of nature. A faculty that is of importance in all technical and artistic occupations, that gives accuracy to our perceptions, and justness to our generalizations, is starved by lazy disuse, instead of being cultivated judiciously in such a way as will on the whole bring the best return.

Introduction

Chemists have long used spatial abilities, such as visualizing 3-D structures and processes from 2-D representations, using rotations and reflections, or identifying and characterizing stereo centers. In the classroom, students learn molecular geometry, how to draw organic structures in a variety of formats, stereochemistry, and group theory. All these concepts require the engagement of spatial abilities, but as Galton noted in 1880, spatial abilities are "starved by lazy disuse, instead of being cultivated judiciously in such a way as will on the whole bring the best return" *(1)*.

It is instructive to review the literature on spatial ability to build an understanding of its relevance and connection to chemistry. Thus, we review the foundational literature on spatial abilities citing origins and assessments. The findings of two large, frequently cited meta-analytic studies are described as a way to address understandings developed within the research base and to elucidate those spatial ability factors that are frequently cited. Examples of spatial abilities tests are presented to help the reader understand the tasks students and adults are asked to complete. A brief review of the sex differences literature with an emphasis on the current research based understanding of differences in spatial abilities between men and women is presented. We connect this literature to studies in chemistry and conclude with implications for instruction in chemistry synthesized across the literature.

Historical Foundations of Spatial Ability

Investigations of spatial ability, as an area of research on intelligence, began to grow in the 1800s. The early work of Sir Frances Galton focused on discovering how people differ in their "mental disposition" through the use of mental imagery *(1)*. According to Galton, mental imagery is "the different degrees of vividness with which different persons have the faculty of recalling familiar scenes under the form of mental pictures, and the peculiarities of the mental visions of different persons". In order to examine mental imagery he used his "breakfast table" experiment wherein he asked participants to think of an object, such as their breakfast table, and then he would ask them several questions about the image in their mind.

Prior to the 1900s, intellectual capabilities were described in terms of a single index of general intelligence *(2)*. In the 1920s, methods in factor analysis were developed that lead to the isolation of a factor different from general intelligence that was designated as a spatial factor. MacFarlane *(3)*, Spearman *(4)*, and El-Koussy *(5)*, in Britain, and Kelley *(6)*, and Thurstone *(7)* in the United States carried out work that lead to the identification of spatial factors.

From the 1930s to the 1970s, research focused on defining the major and minor factors of spatial ability *(8−10)*. An initial period of research from 1925 to 1938 established spatial ability as a factor apart from general intelligence. However, as factor analytic methods were developed, spatial ability was parsed into an array of factors. This era of research resulted in a multitude of factors and terminology that did not yield a clear taxonomy of spatial abilities.

The confusion about factors can be demonstrated by tracing the name of factors associated with rotation across 46 years of research. In 1947, Guilford and Lacy identified two major factors, spatial visualization and spatial orientation, in which the former was described as including "the rotation of depicted objects" *(8)*. Thurstone, in 1950, defined an S1 factor via rotations through the ability to identify an object as seen from different angles, such as a front, top, and side views *(2)*. In Lohman's 1979 meta-analysis, the spatial relations factor contained rotation of objects; however, in 1988, he changed the factor name to speeded rotation *(11, 12)*. Carroll's 1993 meta-analysis produced five major factors, including spatial relations, which pertained to the rotation of objects *(13)*. Thus, a factor pertaining to rotation transitioned from spatial visualization, to S1, to spatial relations, to speeded rotation, and back to spatial relations.

In the 1960s, research on spatial abilities branched off into three different directions—a focus on the development of spatial abilities, identification of sources of variance, and the reanalysis of data using common methodological frameworks. For example, some researchers used an information processing perspective to understand the development and use of spatial cognition *(14)* . Others were interested in differences in performance on spatial ability instruments between boys and girls, and men and women *(15−20)*. The quest to identify tests that demonstrated

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significant differences between males and females, and subsequent attempts to explain the origins of those differences led to a vast amount of research and conjecture. Finally, researchers returned to previously published data sets and used common factor analytic methods to carry out meta-analyses. The purpose of these meta-analytic studies in some cases was to identify major and minor spatial ability factors, and in others to identify which tests produced significant differences between men and women. It is instructive to consider two meta-analytic studies that define major and minor spatial ability factors.

The Meta-Analysis of Factor Analytic Studies in Spatial Ability

Two meta-analytic studies are often cited, Lohman's *(11)* and Carroll's *(12)*, which originated from the development of factor analytic techniques and the movement of the spatial ability field toward reanalysis of prior work. Both included a substantial number of historically important data sets for reanalysis. Perhaps not surprisingly, the factors of spatial ability found in each meta-analysis were not in complete agreement.

Lohman defined spatial ability as (*11*, p 126−127):

> [T]he ability to generate, retain, and manipulate abstract visual images. At the most basic level, spatial thinking requires the ability to encode, remember, transform, and match spatial stimuli.

Lohman set out to determine which factors could be identified as major dimensions of spatial ability—those that emerged again and again in the reanalysis. He found major and minor factors, some of which were identified in the original studies. Three major factors emerged repeatedly and are described below.

- Spatial Relations: This factor is composed of tasks that require mental rotation of an object either in plane (2-D) or out of plane (3-D). He noted that the speed of rotation was probably not part of this factor.
- Spatial Orientation: This factor involves the ability to imagine how an object or array would look from a different perspective by reorienting the observer. These tasks are difficult to design because many can be solved by rotation rather than altering perspective.
- Visualizations: This factor is composed tasks that have a spatial-figural component such as movement or displacement of parts of the figure, and are more complex than relations or orientation tasks.

Lohman also found evidence for the existence of four minor factors he defined as "closure speed" (i.e., speed of matching incomplete visual stimuli with their long-term memory representations), perceptual speed (speed of matching visual stimuli), visual memory (short-term memory of visual stimuli), and kinesthetic (speed of making left−right discrimination) (*11*, p 189).

Carroll's 1993 meta-analysis of spatial ability considered a corpus of 230 data sets and yielded five major factors *(13)*. The spatial relations and the visualizations factors were identical to Lohman's descriptions. The three remaining are described below:

- Closure Speed: The ability to identify a partially obscured or vague object without knowing the identity of the object in advance.
- Flexibility of Closure: The ability to disembed a specific hidden or obscured figure or figures (or patterns) in a larger, more complex figure. This is sometimes referred to by other researchers as field independence or disembedding.
- Perceptual Speed: The speed in finding a unique item in a group of identical items, a specific visual pattern in a visual field, or in accurately comparing one or more patterns when the items or patterns are not obscured.

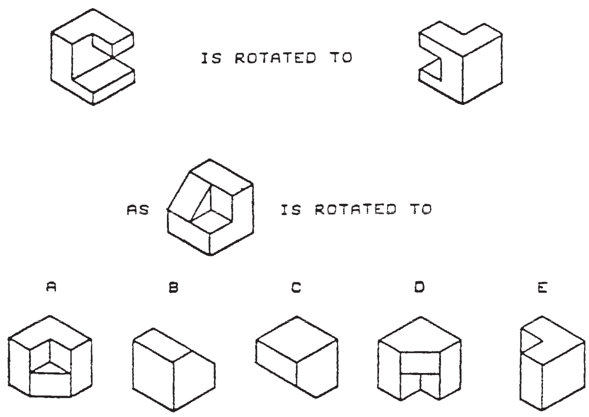

Figure 1. Item number 7 from the PVROT *(27)*, courtesy of *The Chemical Educator* at http://www.chemeducator.org/ (accessed Nov 2010).

Although Lohman's and Carroll's meta-analyses are frequently cited to identify factors of spatial ability, the debate over major and minor factors continues today. Confusion remains as to what the factors actually are, and whether they are separable and measurable. Understandably, researchers have expressed frustration over the lack of a coherent taxonomy *(21)*.

Research in spatial abilities has continued to discover new factors and to spawn new spatial ability tests associated with these factors. One that may be of interest to chemists is dynamic spatial ability. Dynamic spatial ability was first identified by Pellegrino *(22, 23)* and is usually measured on computerized tests of arrival time, such as identifying when a moving object will reach a target, or intercept tasks in which two moving objects are manipulated to arrive at a target simultaneously. Research on particulate animations, such as that done by Tasker and Williamson in particular, may be associated with such abilities *(24−26)*.

Examples of Spatial Ability Tests

The following examples are tests used to measure three common factors of spatial ability—spatial relations, orientations, and visualizations. Work in spatial abilities from the 1930s to the 1970s led to the development of a plethora of pencil-and-paper instruments for measuring spatial abilities, and some work continues in the area today.

Spatial relations can be measured by a variety of rotation tests. In chemistry, the Bodner and Guay *(27)* Purdue Visualization of Rotation Test (PVROT) is frequently used. In the example shown in Figure 1, the task is to discern how the block in the first row is rotated, then perform the same rotation(s) on the test item and chose its appearance from the responses. The subjects taking the test may not make any marks on the paper to help them track the rotation of the block, for example, by making a light pencil mark on the lower right-hand corner of the block. The test subjects must rotate the block mentally.

Outside of the field of chemistry, the Vandenburg and Kuse Mental Rotations Test (MRT) is frequently used *(28)*. The test

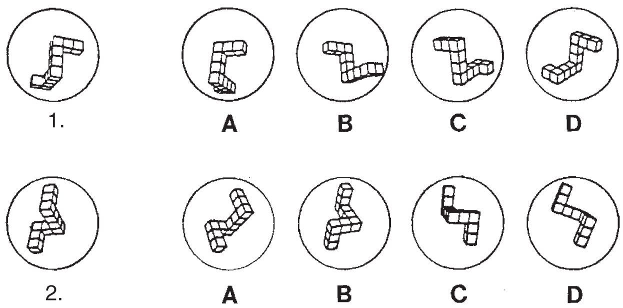

Figure 2. Items 1 and 2 from the redrawn Vandenburg and Kuse Mental Rotations Test *(29)*. Published with permission.

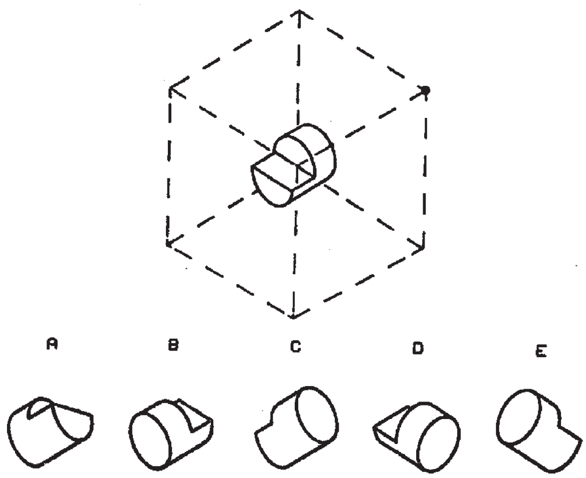

Figure 3. Item 26 from Guay's PSVT: Views section *(30)*. Imagine what the object inside the clear box looks like from the corner of the cube marked with a dot. Used with permission from ref *30*. Copyright 1777 Purdue Research Foundation.

consists of items where a block figure is presented, then rotated along one or two axes. The task is to chose which two of the four responses are identical to the given block arrangement. Two items are shown in Figure 2 from the MRT, which is also available in a re-drawn format *(29)*.

Spatial orientations tests were originally criticized because subjects could solve them by simply rotating the object. Guay tried to address this issue in 1976 when he developed and validated the Purdue Spatial Visualization Test (PSVT) consisting of development (visualization), rotation, and view (orientation) sections*(30)*. The view—orientation section required the subjects to imagine viewing an object from a different perspective, a different corner of a transparent cube as shown in Figure 3.

Recently Hegarty, Kozhevnikov, and Waller developed the Perspective Taking/Spatial Orientation Test *(31—33)* as shown in Figure 4. It is a pencil-and-paper test in which a subject is oriented in the array by being told to imagine standing at one specified object while facing another specified object. The subject imagines pointing to a third specified object. On the test paper, the location where the subject stands is identified in the center of the circle, and an arrow is drawn showing the direction of the third object. The subject is not allowed to make marks on the array of objects, or to turn the test booklet.

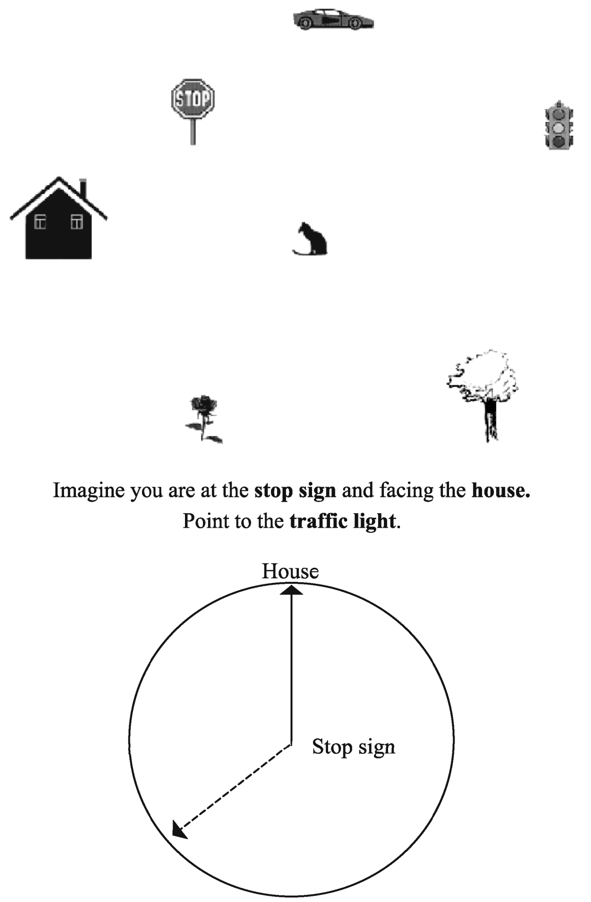

Figure 4. A sample item solved from the Perspective Taking/Spatial Orientation Test (*31*, p 178). Reprinted with permission from ref *31*. Copyright 2004 Elsevier, Inc.

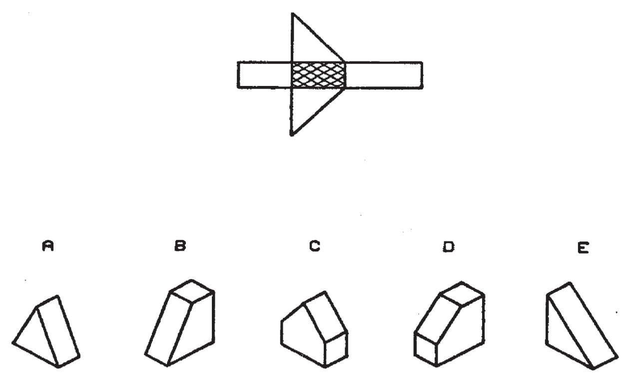

Figure 5. From Guay's *(27)* PSVT: Developments section *(30)*. Fold the development to make a three-dimensional object. Used with permission from ref *30*. Copyright 1777 Purdue Research Foundation.

Spatial visualization tests are more complex than rotation or orientation tasks. Figure 5 shows a spatial development task from Guay's PSVT: Developments section *(30)*. The task in the test is to visualize the folding of a "development" into a three-dimensional object. The initial picture shows the inside of the development and the shaded portion indicates the bottom of the object. For this task, the goal is to picture in your mind what the development looks like when folded into a three-dimensional

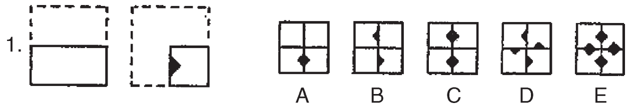

Figure 6. Sample item from Guilford and Lacy's paper-folding test. Reprinted from ref *8*.

object, then choose from among the five objects the one that looks like the folded development. Note that the responses are also rotated from the initial unfolded image.

Guilford and Lacy *(8)* also developed visualization tasks and tests. Figure 6 shows a paper-folding task. Imagine that a piece of paper is folded as shown, and a triangular cut is made in the side as denoted by a black triangle. The task is to choose the response that looks like the paper when it is unfolded. This requires a subject to keep track of the folds, the location of the hole, and the propagation of the hole to other regions of the paper.

These items give a sample of the wide variety of spatial ability tests that have been developed. One of the best sources of reliable and valid spatial ability tests developed prior to 1983 is the International Directory of Spatial Tests *(34)*. This reference volume contains a wide variety of tests classified based upon the test stimulus and requirements, and it stands as a major and influential work in the field.

A Cautionary Note about Spatial Ability Tests

It is well established in the spatial ability research literature that subjects solve complex spatial tasks using different strategies *(11)*. This switching of approaches complicates the interpretation of any spatial ability test because the validity of the test hinges on the assumption that all subjects solve the tasks using the same strategy. In fact, it is possible to solve some spatial ability tasks without using the ability it was designed to measure, thus, rendering the test invalid; spatial orientation tasks can be particularly vulnerable to different strategies such as rotation rather than a change in perspective.

Sex Differences in Spatial Abilities

Although the early research suggested that "males have decidedly better spatial skill than females" *(35)*, today the research literature presents a clearer description of those differences *(15−20, 36)*. The distinction in performance between males and females depends on the specific spatial ability test used and the cognitive components required to perform the test. The largest differences are found in tasks involving 3-D rotation that show effect sizes of nearly 1.0 standard deviations *(36)*. (An effect size is measured as the difference between means expressed in terms of standard deviation units; in this instance, the mean for males minus the mean for females, divided by the SD.)

The differential literature has been reviewed and reanalyzed in an effort to define the difference in spatial abilities between boys and girls *(15−20, 36)*. Across the body of literature there is conjecture as to the origin of the differences, but there is little agreement among these researchers as to the developmental or physiological origins.

Beyond questions about the nature and origins of spatial ability differences, researchers have asked whether the differences in spatial ability have increased, decreased, or remained the same over time. To address this trending issue, Voyer, Voyer, and Bryden *(37)* carried out an analysis of year of birth and magnitude of sex difference as part of a meta-analysis of sex differences in spatial ability.

They found a nonsignificant negative relationship between year of birth and magnitude of sex difference ($z = -1.36$, $p > 0.05$) when 12 tests of spatial ability were entered into the analysis. Significant results for a negative linear relationship between year of birth and magnitude of sex difference were found on specific spatial ability tests, including the cards rotation test, water level test, embedded figures test, and identical blocks test *(34)*. Thus, the data indicate that on some tests sex differences in spatial ability are decreasing.

It is interesting to note that, on the MRT *(28)*, the authors found a significant positive relationship between year of birth and magnitude of sex difference ($z = 6.26$, $p < 0.05$). Further, the aggregated effect size for tasks involving in-plane rotation was 0.56 and for tasks involving 3-D rotation was 0.94. Thus, it appears that significant sex differences exist for rotation and are not diminishing.

Can Spatial Ability Be Improved?

The question of whether or not practice (repeated testing) or specific training (learning or having experience with strategies that are not assessed on the task) can improve spatial ability has been at the center of an on-going debate. Although some researchers question training effects, many more researchers advocate the use of training to improve spatial ability. The heart of this controversy hinges on accepting or not accepting that spatial ability is an innate ability rather than a trainable skill. However, much of the literature shows that spatial ability develops over a person's lifetime, and that interventions can improve spatial ability *(38−41)*.

The training and improvement debate originated from the quantitative methodologies researchers historically used. The methods proved to be a major stumbling block to the field when alternative strategies to solving spatial ability tasks became a source of concern. Researchers had assumed that all participants used the same strategy to solve spatial ability tasks and continued to use quantitative measures that did little to shed light on differing strategies.

It was not until researchers began using qualitative methodologies that strategies could be described and that the effect of training could truly be discerned. As qualitative methods were used (these were and are called "introspective" or "retrospective" reports by subjects), researchers found that subjects did not use the same strategy on specific test items, and often switched strategies based upon item complexity. For example, Myers in 1958 found that subjects reported using imagery techniques (also called gestalt or "wholes") to solve easy surface development problems, and switched to analytic techniques when faced with more complex tasks *(42)*.

Once strategies emerged, training studies could be designed using differing treatments. Many of these experiments used training strategies known as "visualization" in which subjects were trained in rotation using the "whole" object, or "analytic" strategies in which specific methods that relied on analyzing the figure were taught. Kyllonen, Lohman, and Snow *(43)* used a paper-folding task for training studies in which subjects received training in either a visualization or an analytic strategy. They found that high spatial ability subjects benefited the most from practicing tasks and receiving feedback. Low spatial ability subjects benefited the most from training with the visualization strategy. The researchers concluded that training was beneficial especially when the cognitive strengths and abilities of specific subjects were taken into account.

A meta-analysis of training studies by Baenninger and Newcombe demonstrated that (*44*, p 340) "training should be of at least medium duration, ...more task specific training may be better, although generalizability remains an issue, and ...there are no significant sex-related differences in improvement after training".

Terlecki, Newcombe, and Little *(38)* also demonstrated that improvement gained through training is durable, and that persistent training on rotation tasks is most important for women (*38*, p 1010):

> These results show that spatial ability is malleable regardless of gender or previous spatial experience, which is especially important for low spatial experience women, and that the effects of training with such materials can be long lasting. This demonstration is vital to the idea that all individuals can potentially improve their spatial skills given appropriate practice or training, and that superior ability is not a prerequisite for success *(45)*. The data also suggest the importance of sustained and distributed training and education for spatial skill.

Thus, the research has demonstrated that spatial abilities are not immutable; rather, they can be improved.

In science and engineering Sorby's longitudinal studies demonstrate the impact of developing 3-D spatial skills, especially for women *(41)*. Michigan Technological University developed a one-semester lecture plus laboratory course designed to help students improve their spatial abilities. Students who scored less than 60% on the Purdue Spatial Visualization Test: Rotations *(30)* populated the course, although not every student who failed the PSVT:R opted to take the course. A longitudinal study of university retention rates found that women who took the course graduated at significantly higher rates than those who did not, and that the engineering retention rate was significantly higher for women who took the course than for those who did not and failed the PSVT:R. Thus, it appears developing spatial ability has an enduring positive impact on women.

How Are Spatial Abilities Related to STEM and Chemistry?

Spatial abilities have long been recognized as important for success in many occupations *(40, 46)*; spatial abilities play an important role in every STEM (science, technology, engineering, and mathematics) major. Sorby's longitudinal studies included a comparison of grades in follow-on courses taken after a one-semester spatial ability course *(41)*. In a study with robust sample sizes, students who had taken the spatial ability course earned significantly higher grades in calculus I and physics I, and higher grades in chemistry I, although those grades were marginally significant.

Spatial abilities also play a predictive role in the choice of STEM major and STEM careers *(21, 47)*. Even though success in STEM and other disciplines rests upon specific spatial abilities, educators often fail to develop their students' spatial skills *(36, 40, 41)*.

Examples from Chemistry

Discourse in chemistry can be characterized by interactions between students and faculty, texts, and multimedia where a key visual aspect is the rendering of molecules. Teaching and learning of chemistry between students and faculty is mediated by representations of molecules, reactions, and theories in which spatial abilities play a role. Consider the examples listed below, and in Figure 7:

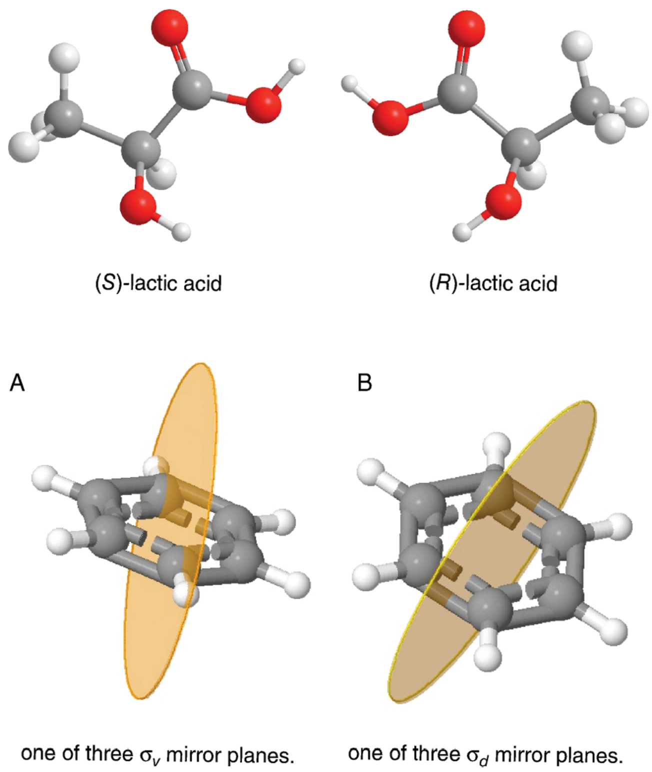

Figure 7. Examples of visuospatial skills used in organic chemistry and group theory when considering molecular representations of lactic acid and benzene. Example 1 (top), enantiomers of lactic acid, or 2-hydroxypropanoic acid; example 2 (bottom), The mirror planes for benzene, C_6H_6, which is in the D_{6h} point group. Reprinted with permission from ref *48*. Copyright 2008 Dean H. Johnston and Otterbein College.

- General chemistry: VSEPR and molecular geometry, kinetic molecular theory, stoichiometry represented at the particulate level, and crystal structure
- Organic chemistry: S_N2 reactions, chirality, stereochemistry, and the different methods of representing molecules such as Newman, Fisher, and Haworth projections, boat and chair conformers, skeleton diagrams, and so forth
- Group theory (inorganic and physical chemistry): Symmetry elements—identity, *n*-fold rotational axes, mirror planes (reflection), inversion, improper *n*-fold rotation, dihedral planes—and their associated operations
- Biochemistry: Shapes of biomolecules and enzyme–substrate interactions

For the examples in Figure 7 to be meaningful, spatial skills and conceptual knowledge of chemistry must be integrated. Organic chemists often use lactic acid to demonstrate stereoisomerism, as shown in Figure 7, Example 1. The compound $C_3H_6O_3$ exists as enantiomers, (*S*)-lactic acid and (*R*)-lactic acid, of which the latter is biologically relevant. Students are expected to recognize the chiral carbon and identify it from different renderings, such as skeleton drawings or ball-and-stick models. Further, students would be expected to apply spatial skills in order to understand that the two images of lactic acid in Figure 7, Example 1 are nonsuperimposable mirror images, and thus are different molecules.

Benzene belongs to the D_{6h} point group, which has vertical and dihedral mirror planes as symmetry elements, as shown in Figure 7, Example 2. In group theory, logical–visual spatial skills dominate the content to be mastered by students *(49)*. Significant spatial skills, including visualization and rotation (i.e., spatial relations), are required to identify symmetry elements and place molecules in point groups. These skills are then partnered with conceptual knowledge to predict vibrational spectra and chirality.

Representational Competence in Chemistry

Chemists use a wide variety of methods to represent concepts in chemistry. In order to move between representations and to use them as data in arguments to support claims, they must develop a set of representational competencies *(50, 51)*. Kozma et al. describe six representational competencies to be developed by students, three of which overlap with spatial abilities (*50*, p 136):

- Generate representations that express their understanding of underlying entities and processes
- Use these representations to explain chemical phenomena at the observable, physical level in terms of chemistry at the particulate (i.e., molecular and structural) level
- Identify and analyze features of representations (such as a peak on a graph) and use them to explain, draw inferences, and make predictions about chemical phenomena or concepts

Drawing molecular representations and using them to explain physically observable phenomena requires the development of spatial abilities and an understanding of chemistry content. This ability has been referred to as "visuospatial skills" by other researchers in chemistry, and represents the ability to generate and recognize drawings of molecules and symbols, and to correctly reason with them. Representational competence encompasses a broader range of skills in which the ability to generate molecular images is partnered with chemistry content and the ability to analyze, evaluate, and synthesize data. Thus, spatial abilities in chemistry are denoted frequently as visuospatial skills, and as Kozma's notion of representational competence makes clear, they are required to facilitate and mediate communication in chemistry.

Research on the Relationship between Spatial Abilities and Chemistry Performance

Research that has focused on visuospatial skills in chemistry has uncovered specific student difficulties in comprehending, interpreting, and translating molecular representations. Many students are not able to provide an equivalent representation for a specific representation because of insufficient content knowledge *(52)* or a lack of visuospatial skills *(53)*.

Several researchers have found that rotation and reflection transformations are particularly troublesome for students. Krajcik found that many students who could form a 3-D representation of a 2-D image could not mentally rotate it accurately *(54)*. Similarly, both Tuckey et al., and Shubbar, in separate studies, found that among students who could correctly interpret depth cues, few could mentally track how those cues changed as the molecule was rotated about an axis or reflected through a plane *(53, 55)*. The ability to interpret depth cues and to rotate or reflect the representation of a molecule plays a key role in understanding a wide array of chemical knowledge and concepts from areas as diverse as organic synthesis *(56–58)* ,biochemistry, and group theory *(48)*.

Tasks that require rotation have demonstrated a well-defined empirical fingerprint *(13, 59)*. As the angle of separation between the stimulus figure and the target figure increases from 0° to 180°, the response time (also known as response latency) linearly increases *(59–62)*. In cases where the subject can solve the problem without using mental rotation, the response time decreases and the positive linear relationship between response time and angle of separation disappears.

Stieff used the response time relationship to investigate mental rotation and diagrammatic reasoning in organic chemistry *(59)*. His results demonstrated that experts (Ph.D. chemists) used an analytical strategy on all symmetrical objects (molecules or block diagrams) that allowed them to solve rotation tasks more rapidly. The experts searched for symmetry planes or analyzed molecular structures for chiral carbons. All asymmetric objects were solved using rotation of the whole object and showed a linear relationship between response time and angle of disparity.

The students in this study demonstrated interesting strategy choices *(59)*. All used mental rotation for asymmetric objects, whether block diagrams or molecular structures. However, not all students used the analytical strategy—searching for symmetry planes or chiral carbons—for symmetric objects. Some used it only on molecules but not on block diagrams, one student used it on block diagrams, but not on molecules. Stieff concluded that the analytical strategy is tied to the organic chemistry classroom context for some students, but not all. He noted that knowledge of the strategy is not enough to guarantee its use in the chemistry classroom, as evidenced by the student who used it on block diagrams but not on molecular structures. Stieff also showed that students were able to learn the analytical strategy and apply it appropriately. The most important outcome of Stieff's research is that visuospatial strategies are used until domain-specific strategies are learned or discovered. He noted (*59*, p 232):

> Such use is supported by the expert chemists' uniform application of the analytical strategy in all symmetrical tasks. Whether these experts developed a predilection for the analytical strategy as a result of experience or from a particular moment of insight is not clear from the instantaneous measure used in the present work. What is evident, however, is that experts apply the analytical strategy as a first step in their solution strategy before using mental rotation. This suggests that analytical strategies may become dominant as expertise grows, thereby decreasing a reliance on mental rotation or other forms of visuo-spatial reasoning.

He went on to write that mental rotation is not a prerequisite for success in organic chemistry, and that students can learn to apply analytical skills when warranted.

Other researchers have carried out correlation studies on rotational ability and achievement in organic chemistry. Cooper and Grove *(63)* discovered a slight (r = 0.209, $p < 0.05$) but significant relationship between rotation as measured by the PVRT *(27)* and achievement on the 2004 ACS organic chemistry exam *(64)*.

Tuckey et al. *(53)* hypothesized that translation between 2-D and 3-D representation required a stepwise approach. They deconstructed the approach into cognitive components and tested student understanding of each component. Translation between 2-D and 3-D representations required students to respond to depth cues such as foreshortened lines, relative sizes of different parts of the molecule, representations of bond angles, and the extent to which overlap occurs. They found that many students were unable to respond to depth cues.

They created a 2-h workshop to address student difficulties that related to recognition of depth cues, overlap and foreshortened lines, wedge and dash cues, identification of axes, rotation about axes, and reflection through mirror planes. ANCOVA results demonstrated significant difference on posttest scores between students in the group receiving the 2-h workshop and those who did not. The F value, $F(1,28) = 10.67$, $p < 0.01$, with pretest scores as covariates, demonstrated the value of engaging students in practice related to the rotation and reflection of molecular structures. Further, they found no significant differences in the pretest and posttest performances in the experimental group between male and female students.

Bodner and McMillen *(65)* demonstrated a statistically significant correlation of $r = 0.32$, ($p < 0.0001$, $N = 587$) between the sum of t-test scores from four spatial ability tests (the PVROT, ref *27*; the Find-A-Shape-Puzzle, FASP, refs *66* and *67*; the embedded figures test; and the successive figures test, ref *68*) and multiple-choice crystal structure exam questions, and a statistically significant correlation of $r = 0.35$ ($p < 0.0001$, $N = 587$) between the same sum of t-test scores and a free-response quiz score on crystal structure. According to Guilford (*69*, p 145), these correlations are low to moderate, yet a definite, albeit small, relationship exists between the variables.

Bodner and Pribyl *(58)* found significant main effects between the sum of t-test scores from two spatial ability tests (PVROT and FASP) and performance on organic chemistry exam questions that required students to carry out one of the following tasks:

1. Use, draw, or name structural formulas or transform between representations of molecules (either projections, names, or structural formulas)
2. Identify what is missing or wrong in a particular molecular structure or formula
3. Complete a synthesis either by specifying reactants, and reagents, or proposing an entire multistep synthetic route
4. Analyze the 3-D structure of a molecule (e.g., optical activity)

Associated with this study was the observation that high spatial ability students (defined as one-half of a standard deviation above the mean total spatial ability score) repeatedly drew molecular representations to solve structural problems of the type described in 1 above, or synthesis problems as described in 3. Low spatial ability students did not engage in the same representational activities. They were less likely to draw skeleton diagrams, and those that were drawn were often poorly formed and asymmetric. They also were more likely to give symbolic representations of reagents and intermediates in multistep syntheses rather than molecular structures.

Differences in problem solving between high and low spatial ability students have manifested themselves in other STEM settings. The observation that high spatial ability students decompose objects as a problem-solving strategy while low spatial ability students struggle or are unable to carry out this same strategy has been demonstrated with engineering students *(70−72)*.

Carter, Larussa, and Bodner *(73)* found that general chemistry students with high spatial ability significantly outperformed students with low spatial ability on molecular geometry and crystal structure exam questions. (Again, high spatial ability was defined as one-half of a standard deviation above the mean total spatial ability score comprised of the sum of t-test scores from the PVROT and FASP.) There was a significant effect of spatial ability on exam subset performance for molecular geometry at the $p < 0.01$ level for the three conditions ($F = 4.67$), and a significant effect of spatial ability on exam subset performance for crystal structure questions at the $p < 0.001$ level for the three conditions ($F = 12.87$). The correlations that were significant (either at the $p < 0.01$ or $p < 0.001$ level) between the exam subset and either the PVROT, FASP, or total spatial score were 0.20 and below.

Literature-Based Implications for Improving Spatial Ability in Chemistry

One of the problems students face when taking a course that requires the use of spatial skills is that instruction may not directly help them learn how to use domain-specific visuospatial skills to solve problems. Halpern and Collaer wrote that "the development of these abilities has been largely ignored in education and training programs" (*36*, p 204). Thus, in chemistry, the challenge for faculty is to help students become competent in the domain-specific spatial skills that are key to connecting the particulate representations of molecules to conceptual and symbolic knowledge.

Research in chemistry, engineering, and cognitive science has demonstrated that high spatial ability and low spatial ability learners differ in the quality of the spatial representations that they are able to construct *(32, 72)*. Mohler suggests that teaching students how to "strategically dissect spatial problems" may play an important role for helping low spatial ability learners solve problems *(72)*. Schonborn and Anderson emphasize that "students do not automatically acquire visual literacy during general instruction" so it is "essential to explicitly teach and assess this type of knowledge" *(74)*. Finally, Sorby's work in engineering makes it clear that there is a positive enduring impact on students, especially women, in terms of retention rates and success in science and mathematics courses associated with developing spatial abilities *(41)*.

Synthesizing across the spatial ability literature and the research on spatial ability in chemistry allows us to identify recommendations for instruction in chemistry.

Explicitly Articulate Three-Dimensional Cues

Chemistry has a spatial language that students must master. Faculty should frequently draw and describe 2-D representations that are encoded with 3-D cues such as wedge-dash notation, foreshortened lines, distorted angles, and so on, to promote students' ability to visualize 2-D and 3-D representations of molecules. Students should be required to construct and describe 2-D representations that are encoded with 3-D cues such as wedge-dash notation, foreshortened lines, distorted angles, and so forth to connect particulate drawings to the spatial and conceptual knowledge they convey. Research indicates that this type of training and development is durable *(38, 41)*. Thus, repeated practice with molecular structures is critical to build an understanding of the encoded conceptual and structural information.

Provide Ongoing Instruction on Molecular Representation

Students should receive direct instruction in transformation between chemical formulas (symbolic representations), and 2-D and 3-D representations of molecules. Depiction of conceptual knowledge such as chemical formulas as 2-D structures with appropriately embedded 3-D cues should be integrated into lectures, recitations, and laboratories across the semester.

Bodner and Pribyl *(58)* found that in organic chemistry students with high spatial ability drew appropriate molecular representations for chemical formulas when solving problems. This translation between symbols and molecular representations led to greater success in organic problem solving. Thus, focusing on the connection between symbolic and particulate representations of molecules should help students become more successful.

This recommendation is also in accordance with Johnstone's prior work in chemistry, structuring the field in macroscopic, submacroscopic or particulate, and symbolic domains *(75−77)*. The particulate domain is the most difficult for students to grasp and connect meaningfully to the symbolic and macroscopic.

Continuously Demonstrate Visuospatial Analytic Techniques

Faculty should explicitly and repeatedly teach domain-specific visualization skills, thus, helping students to learn to apply analytical techniques in a chemistry context.

Stieff's research in organic chemistry compellingly demonstrated that, even if students knew of the analytical strategy, they did not use it in the organic chemistry classroom *(59)*. Thus, students may need to see these strategies in chemistry contexts in order to recognize when to use them.

Kozma's concept of representational competence encourages faculty to support students building connections between student generated molecular structures and chemical formulas, and molecular structures and physically observable phenomena *(50, 51)*. The linkage between the symbolic and particulate level is simultaneously a part of representational competence and Johnstone's description of the cognitive domains of chemistry *(50, 51, 75−77)*. For example, molecular structures can serve as warrants to claims made based upon empirical data such as NMR or FTIR spectra. This linkage between the macroscopically observable phenomena and particulate level is also simultaneously part of representational competence and Johnstone's model *(75−77)*.

Teach students how to use mnemonic devices to lower the cognitive load of transforming and visualizing molecules. For example, the trick for remembering how to transform the Fischer projection of glucose to a pyranose is “if you left it up to me, I′d have to write (right) it down”. This mnemonic allows students to analytically approach the transformation where the substituents on the left are drawn up, and on the right are drawn down.

Terlecki et al. *(38)* and Sorby *(41)* demonstrated that training is durable and is helpful to lower spatial ability students and women. Thus, explicitly teaching domain-specific strategies repeatedly across the semester should prove to be durable and improve student performance on these tasks.

Provide Visualization Resources for Students To Practice Spatial Ability Skills

Johnson's online symmetry tutorial *(48)* incorporates five design principles for visualization tools described by Wu and Shah *(48, 78)*. For group theory, this tutorial provides multiple representations and descriptions, links conceptual entities to molecular structure, promotes transfer of symbolic information to 3-D molecular structures, and makes symmetry elements and operations dynamic via Jmol animations. It is an extraordinarily useful visualization tool to help students learn symmetry operations and elements associated with group theory.

Conclusions

Familiarity with the foundational spatial ability literature can assist chemistry faculty in identifying spatial abilities related to chemistry. Synthesizing across research in spatial ability, chemistry education research, and STEM education research allows for the development of recommendations and implications supported by a strong research base. Chemistry faculty should be guided by Galton's admonishment to cultivate visuospatial skills “judiciously in such a way as will on the whole bring the best return” *(1)*.

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