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SPATIAL ABILITY AND ITS ROLE IN ORGANIC CHEMISTRY: A STUDY OF FOUR ORGANIC COURSES

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Abstract

The relationship between spatial ability and performance in organic chemistry was studied in four organic chemistry courses designed for students with a variety of majors including agriculture, biology, health sciences, pre-med, pre-vet, pharmacy, medicinal chemistry, chemistry, and chemical engineering.

Students with high spatial scores did significantly better on questions which required problem solving skills, such as completing a reaction or outlining a multi-step synthesis, and questions which required students to mentally manipulate two-dimensional representations of a molecule. Spatial ability was not significant, however, for questions which could be answered by rote memory or by the application of simple algorithms.

Students who drew preliminary figures or extra figures when answering questions were more likely to get the correct answer. High spatial ability students were more likely to draw preliminary figures, even for questions that did not explicitly require these drawings. When questions required preliminary or extra figures, low spatial ability students were more likely to draw figures that were incorrect. Low spatial ability students were also more likely to draw structures that were lopsided, ill-proportioned, and nonsymmetric.

The results of this study are interpreted in terms of a model which argues that high spatial ability students are better at the early stages of problem solving described as "understanding" the problem. A model is also discussed which explains why students who draw preliminary or extra figures for questions are more likely to get correct answers.

Introduction

Organic chemistry texts are filled with drawings of stick structures, space-filling models, Newman projections, Fisher projections and other examples of two-dimensional representations of three-dimensional molecules, and there is little doubt that the ability to construct and manipulate three-dimensional men-

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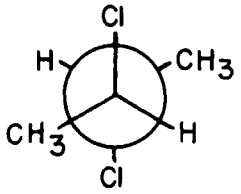
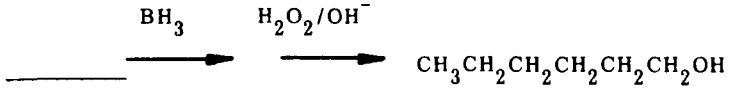
Question 1: Provide the IUPAC name for the following molecule.



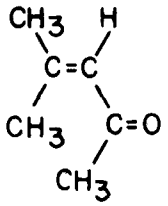
Question 2: Draw the complete structure for Z-2-chloro-2-pentene.

Question 3: Draw structural formulas for all possible isomers of C_4H_9F.

Question 4: Complete the following reaction by drawing the structure(s) of all products or the required reactants.



Question 5: Outline a synthetic procedure for preparing



from isopropyl alcohol

Fig. 1. Selected exam questions taken from the CHM 257 organic chemistry course.

tal images from these drawings is important to organic chemists (Shepard, 1978). What can be questioned, however, is the extent to which this ability plays an important role in the success or failure of students encountering organic chemistry for the first time.

Exam questions which deal with three-dimensional features of a molecule, such as questions 1, 2 and 3 in Figure 1, are best solved by manipulating three-dimensional mental images of the molecules. But other exam questions, such as questions 4 and 5 in Figure 1, might be answered just as easily by manipulating the two-dimensional stick structures with which organic molecules are depicted.

Previous work has suggested a relationship between spatial ability and achievement in chemistry. Bodner and McMillen (1986) found a correlation between tests of spatial ability and achievement in general chemistry on both spatial and nonspatial tasks. Bowen and Barsalou (in press) found that spatial ability can account for up to 10% of the variance in final exam scores in a first-

TABLE I
Mean, Standard Deviation and Reliability Data for the ROT and FASP Tests

		CHM 255 (n = 158)	CHM 257 (n = 127)	CHM 261 (n = 69)	MDCH 204 (n = 68)
ROT					
	x	14.2	12.3	13.7	12.8
	σ	3.8	4.0	3.7	4.4
	r[a]	0.78	0.84	0.81	0.81
FASP					
	x	14.3	12.8	13.7	11.9
	σ	4.4	4.7	4.8	5.7
	r[b]	0.83	0.84	0.78	0.90

[a] Split-half (odd–even) reliability coefficient.
[b] Estimate of reliability calculated using Cronbach's alpha formula.

semester organic course. Small and Morton (1983) found that spatial training improves performance on spatial tasks in organic chemistry, but not on nonspatial tasks. This study was designed to investigate the extent to which spatial ability, including the ability to construct and manipulate three-dimensional images of two-dimensional drawings, affects performance across a spectrum of organic courses encompassing a range of student abilities, interests and backgrounds.

Method

Spatial Ability Tests

Two tests were used to measure spatial ability: the 20-item version of the Purdue Visualization of Rotations test (Bodner, Carter, & Guay, in press) and the 20-item Find-A-Shape-Puzzle (Linn, Pulos, & Gans, 1981; Linn & Kyllonen, 1981). Mean, standard deviation and reliability data for the ROT and FASP tests are given in Table I.

The Purdue Visualization of Rotations (ROT) test asks students to: (1) study how the object in the top line of the question is rotated, (2) picture in your mind what the object shown in the middle line of the question looks like when rotated in exactly the same manner, and (3) select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position. Item 7 from this test is shown in Figure 2. A time limit of 10 minutes for the ROT test was used in this study to restrict analytical processing.

The Find-A-Shape-Puzzle (FASP) is an adaptation of Gottschaldt's Hidden Figures test. It consists of four pages, one of which is shown in Figure 3. The

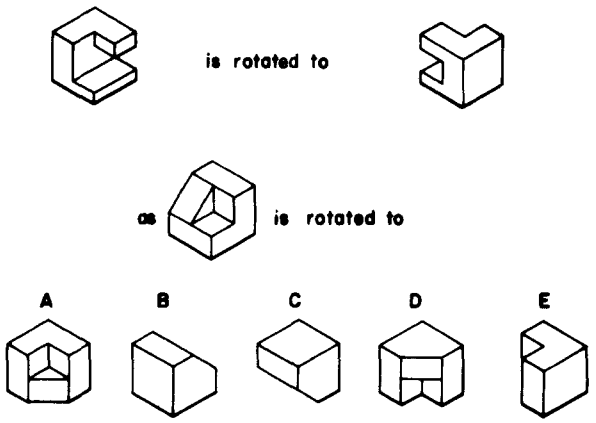


Fig. 2. Item 7 from the 20-item version of the Purdue Visualization of Rotations (ROT) test.

subjects were given one minute per page to find and shade-in the simple figure in each of the five complex drawings.

Subjects

Four organic chemistry courses at the West Lafayette campus of Purdue University were used in this study. CHM 257 is a one-semester introduction to organic chemistry for agriculture or health science majors. CHM 255, CHM 261 and MDCH 204 are the first halves of two semester organic sequences. CHM

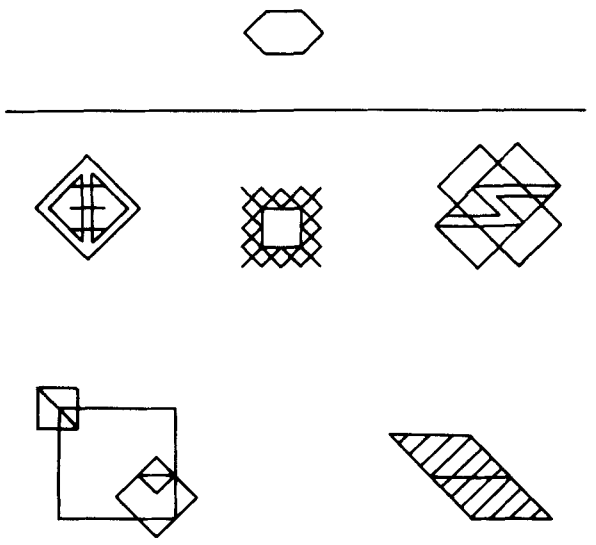


Fig. 3. Page two of a four-page, 20-item test of disembedding in the spatial domain known as the Find-A-Shape-Puzzle.

255 is taken by biology and preprofessional students, CHM 261 is taken by chemistry and chemical engineering majors, and MDCH 204 is taken by students majoring in pharmacy or medicinal chemistry.

The spatial tests were given to students in CHM 255 and 257 during lecture or laboratory in the first week of the semester. Spatial ability scores for students in CHM 261 and MDCH 204 were carried forward from data obtained by Carter (1984) when these students were enrolled in general chemistry.

Chemistry Performance

Regularly scheduled exams were used to measure chemistry performance. Between 4 and 6 exams were given in each course. The exams were written by the professors in charge of the course, and graded by the professors and teaching assistants assigned to the course. The exams had a variety of formats including true-false, multiple-choice, matching, short answer, essay, structure drawing, and formula writing questions. The authors made no attempts to influence the nature of the exams used in this study.

Correlations between student scores on the five exams in CHM 257 were calculated to estimate the reliability of the organic chemistry exams. The correlation coefficients ranged from 0.57 to 0.78, but every correlation was significant at the $p < 0.001$ level.

Statistical Procedure

Student scores on the ROT and FASP exams were converted to standard T-scores, and a total spatial score (TSPAT) was calculated for each student by adding these scores. Students were divided into three groups based on their ROT, FASP or TSPAT scores. Those who scored more than one-half standard deviation below the mean were classified as "low spatial ability", those who scored more than one-half standard deviation above the mean were classified as "high spatial ability", and the remaining students were grouped in a "middle spatial ability" category. The percentage of the sample population in each category varied with the course and the spatial score. However, no group contained less than 22% or more than 50% of the total population, and there was no clear pattern of differences in the distribution of high, middle and low spatial students in the various courses.

ANOVA, Pearson product–moment correlation coefficients, Scheffé's tests and estimates of reliability were calculated using the SPSS program on the Purdue computer system.

Results

Analysis of variance was used to test the hypothesis that there is no significant difference in performance on organic chemistry exams when students are classified by spatial ability and/or sex. When ROT and SEX were used as variables, the ROT main effect was significant on six of the 20 exams, the main effect of SEX was significant in only one case (CHM 255, Exam 1) and the ROT $\times$ SEX interaction term was significant for only one exam (MDCH, Exam 1).

TABLE II
F Values from the Analysis of Variance for TSPAT

	CHM 255	CHM 257	CHM 261	MDCH 204
Exam 1 TSPAT	2.2	7.9*	0.7	3.8*
SEX	4.2*	0.2	1.6	0.0
TSPAT x SEX	0.3	1.7	1.9	0.9
Exam 2 TSPAT	1.1	6.5*	4.4*	0.4
SEX	0.0	0.2	7.2*	0.3
TSPAT x SEX	1.3	3.0	3.6*	0.2
Exam 3 TSPAT	1.9	5.8*	2.1	2.6
SEX	0.0	0.3	2.7	0.8
TSPAT x SEX	0.6	0.3	2.5	1.4
Exam 4 TSPAT	3.6*	4.0*	4.8*	5.6*
SEX	0.2	1.0	1.2	0.1
TSPAT x SEX	1.5	2.4	1.1	0.3
Exam 5 TSPAT	3.7*	5.8*		3.8*
SEX	1.0	1.2		0.3
TSPAT x SEX	1.0	0.6		0.8
Exam 6 TSPAT	2.6			
SEX	0.0			
TSPAT x SEX	3.2*			

* Significant at or below the 0.05 level.

When FASP and SEX were used as variables, FASP was significant for nine exams, SEX was significant for only one exam (CHM 261, Exam 2), and none of the FASP × SEX interaction terms were significant. When total spatial score and SEX were used as variables, TSPAT was significant on 12 exams, two exams had a significant main effect of SEX (CHM 255, Exam 1 and CHM 261, Exam 2), and two exams had a significant TSPAT × SEX interaction term (CHM 261, Exam 2 and CHM 255, Exam 6). Results of this analysis for TSPAT scores are given in Table II. The main effects of ROT, FASP or TSPAT were significant in 9 of 15 cases (60%) for CHM 257; 6 of 12 cases (50%) for CHM 261; 8 of 15 cases (53%) for MDCH 204; but only 5 of 18 cases (28%) for CHM 255.

Pearson product–moment correlation coefficients were calculated for the three spatial scores on each of the organic chemistry exams. Results of these calculations, shown in Table III, suggest that up to 15% of the variance in exam scores can be attributed to spatial ability. With the exception of the fifth exam for CHM 255, correlation coefficients were positive and significant in all cases where significance was found by ANOVA.

Scheffé's test (Scheffé, 1953) was used to determine which groups were different wherever ANOVA suggested a significant difference between the three spatial groups (high, middle and low). In 17 out of 22 cases, the high spatial ability students received chemistry exam scores that were significantly larger than the low spatial ability students.

The five exams in CHM 257 were divided into subscores that grouped

TABLE III
Pearson Product–Moment Correlation Coefficients

	CHM 255	CHM 257	CHM 261	MDCH 204
ROT				
Exam 1	0.06	0.24*	-0.15	0.27*
Exam 2	0.09	0.16*	0.11	0.12
Exam 3	0.02	0.28*	0.03	0.33*
Exam 4	0.07	0.20*	-0.01	0.31*
Exam 5	-0.08	0.19*		0.23*
Exam 6	-0.13			
FASP				
Exam 1	0.19*	0.39*	0.35*	0.16
Exam 2	0.10	0.25*	0.37*	0.07
Exam 3	0.18*	0.23*	0.28*	0.29*
Exam 4	0.21*	0.19*	0.30*	0.28*
Exam 5	0.13	0.23*		0.22*
Exam 6	-0.01			
TSPAT				
Exam 1	0.16*	0.37*	0.08	0.22*
Exam 2	0.08	0.25*	0.28*	0.09
Exam 3	0.15*	0.31*	0.21*	0.28*
Exam 4	0.15*	0.24*	0.20*	0.28*
Exam 5	0.08	0.26*		0.20*
Exam 6	-0.08			

* Significant at or below the 0.05 level.

similar questions to gain insight into the topics or types of questions where spatial ability plays an important role. Subscores were then subjected to an analysis of variance using TSPAT as the variable. The results of this analysis, given in Table IV, show a significant TSPAT main effect on 18 of the 29 subscores.

Discussion

This study supports the hypothesis that there is a small but positive relationship between spatial ability and achievement in organic chemistry (Bowen & Barsalou; Small & Morton) which can explain as much as 15% of the variance in exam scores. Although Maccoby and Jacklin (1974) listed visual-spatial ability as one of only four sex differences that are fairly well established, this study found significant main effects of sex in only 4 of the 60 cases studied, and sex by spatial ability interactions in only 3 of these cases.

This study found differences in the extent to which spatial ability influenced performance in the four organic courses. Analysis of the exam questions suggests that CHM 257 exams required high order cognitive skills or problem solving skills more often than CHM 261 or MDCH 204 exams, and much more often than CHM 255 exams, regardless of whether the questions covered spatial or nonspatial topics. It is therefore interesting to note that the relationship

TABLE IV
F Values from the Analysis of Variance of CHM 257 Exam Subscores Using TSPAT as the Variable

	EXAM 1	EXAM 2	EXAM 3	EXAM 4	EXAM 5
Sub-score 1	0.46 (h)	1.10 (i)	4.72 (c)*	4.51 (c)*	7.32 (b)**
Sub-score 2	9.74 (b)**	5.27 (c)**	0.21 (l)	2.00 (k)	3.52 (f)*
Sub-score 3	7.04 (f)**	3.12 (k)*	2.91 (l)	1.29 (c)	5.12 (g)**
Sub-score 4	8.14 (a)**	4.64 (d)*	4.30 (d)*	3.64 (d)*	3.17 (e)*
Sub-score 5	2.81 (b)	1.32 (j)	1.92 (e)	0.29 (l)	3.16 (c)*
Sub-score 6	3.99 (l)*	3.28 (e)*			2.20 (d)
Sub-score 7		4.45 (b)*			

* Significant at or below the 0.05 level.

** Significant at or below the 0.01 level.

Subscore categories: (a) name compound, (b) draw structure, (c) complete reaction, (d) design multi-step synthesis, (e) 3-D features of molecule, (f) identify missing or wrong entry, (g) higher-order multiple choice questions, (h) draw Lewis structure, (i) predict site of aromatic substitution, (j) decide whether compound is aromatic, (k) write mechanism, (l) knowledge- or comprehension-level multiple choice or fill in the blank questions.

between performance on the spatial ability tests and the organic exams was largest for CHM 257 and smallest for CHM 255.

Remarkably consistent results were obtained when the five CHM 257 exams were broken down into subscores. Significant TSPAT main effects were found on 16 of the 20 subscores that contain questions which fit into six general categories.

(1) Questions which asked students to name compounds from their structural formulas, or draw structural formulas from their names or molecular formulas, such as questions 1, 2, and 3 in Figure 1.
(2) Questions which asked students to complete a reaction or specify the reagent necessary to carry out a transformation, such as question 4 in Figure 1.
(3) Questions which asked students to outline a multi-step synthesis of a given product from a specified starting material, such as question 5 in Figure 1.
(4) Questions which focused on the three-dimensional features of a molecule, such as questions on optical activity.
(5) Questions which gave students a series of chemical formulas or structures and asked them to identify the entry in which something is either missing or wrong.
(6) Higher-order multiple choice questions.

TSPAT was not significant as a main effect on seven of the nine subscores that consisted of questions which fell into three general categories.

(1) Questions which could be answered algorithmically, such as drawing Lewis structures, predicting the site of aromatic substitution, or deciding whether a compound was aromatic.

(2) Questions which asked students to write the mechanism of a reaction discussed in class, such as the free radical chlorination of ethane.
(3) Knowledge- or comprehension-level multiple choice questions, or multiple choice questions that could be answered by the use of algorithms or rote memory.

A subjective analysis of CHM 257 exams showed differences between the work of a representative sample of high and low spatial ability students. With only one exception, the high spatial students answered question 1 in Figure 1 by first drawing a stick structure for the molecule. The low spatial students were less likely to draw a stick structure, and more likely to draw a incorrect structure when they tried to draw a stick structure.

When asked to draw the structure of a compound from its name (such as question 2 in Figure 1), the high spatial students drew a preliminary stick structure before attempting the final structure, and tended to draw final structures that were well-proportioned, with good symmetry and little distortion. The low spatial students were less likely to make preliminary drawings, and more likely to produce a final drawing that was lopsided, ill-proportioned and nonsymmetric.

When asked to complete a reaction by drawing the missing reactants or products, high spatial students tended to draw mechanisms or additional structures which ranged from sketched outlines to accurate figures. When asked, for example, to complete the equation,

$$PhCOOH + SOCl_2 \rightarrow$$

high spatial ability students were more likely to draw preliminary structures in which the "Ph" or phenyl group was represented by a six-membered ring and the "COOH" carboxylic acid group was represented by an —OH group attached to a C=O function. They were also more likely to draw final structures in which the "Ph" group was represented by a six-membered aromatic ring, and the carbonyl group was represented as "C=O". Low spatial ability students were less likely to draw preliminary structures for these questions, which was unfortunate because students who drew additional structures tended to score higher than those who didn't. Low spatial students were also less likely to draw final structures in which the phenyl group was represented by a six-membered ring, and more likely to give final structures such as: "PhCOCl". Low spatial students were also more likely to write equations such as

$$PhCOOH + SOCl_2 \rightarrow PhCl + SO_2 + HCl$$

or

$$PhCOOH + SOCl_2 \rightarrow PhCOOCl + SO_2 + HCl$$

which violate the basic rules of writing balanced chemical equations.

Conclusion

A significant spatial ability main effect was found in this study when: (1) exam questions required students to mentally manipulate two-dimensional representations of molecules, and/or (2) exams focused on higher order cognitive

skills such as problem solving. Spatial ability was not significant when exam questions could be answered by rote memory or by the application of simple algorithms. These observations are consistent with the preliminary results of Bodner and McMillen, and the more extensive results of Carter, LaRussa and Bodner (in press), who found significant correlations between spatial ability ad performance in general chemistry only on questions that required problem solving skills.

Correlations between spatial ability and performance on spatial tasks in organic chemistry confirm our initial hypothesis that these two factors are related. The correlation with performance on problem solving tasks, however, is potentially more significant. Spatial ability has been repeatedly linked with mathematical performance (Hills, 1957; Aiken, 1971; Eisenberg & McGinty, 1977; Fennema & Sherman, 1977; McGee, 1979; Turner, 1982; Battista, Wheatley, & Talsma, 1982). But questions which ask students to predict the products of a chemical reaction or design a multistep synthesis, such as questions 4 and 5 in Figure 1, are not like typical problems in mathematics. They belong to a class of nonmathematical problems that occur routinely in chemistry.

Bodner and McMillen argued that the relationship between spatial ability and problem solving traces back to the early stages of the problem solving process, the stage Polya (1945) described as "understanding". They argued that high spatial students were better at disembedding relevant information from the statement of a problem, and transforming or restructuring the problem into one for which the student can recognize the initial and final or goal states. Evidence for this hypothesis can be obtained by examining differences between the representations of high and low spatial ability students, because a student's degree of understanding is generally assumed to be reflected in the problem representation (Greeno, 1977).

The high spatial students were more likely to develop representations that could be described as "physical" (Paige & Simon, 1966). As noted previously, when asked to predict the products of the reaction between PhCOOH and $SOCl_2$ they drew preliminary figures that contained six-membered phenyl rings and explicit carboxylic acid groups, and they carried this representation over to the figures they drew for the products of this reaction. The low spatial students were far more likely to use "syntactic" representations (Paige and Simon). Symbols such as "Ph" or "CO" were used as encountered without apparent regard to their meanings. These students were therefore more likely to offer unreasonable answers to this question, such as "PhCl + SO_2 + HCl" or "PhCOOCl + SO_2 + HCl".

The representations of high spatial students exhibited more coherence, correspondence and connectedness (Greeno, 1977) in the sense that these representations were more complete, they more accurately portrayed the components of the problem, and they were better connected to the students' other knowledge. This is not surprising, because the ability to perceive relationships and process information holistically has been described as an essential characteristic of spatial ability (Guay, McDaniel, & Angelo, 1978).

Yackel (1984) provided a theoretical basis for understanding why students who draw preliminary figures or additional structures for questions are more likely to get the correct answers. She concluded that diagrams: (1) serve as an

external aid to memory, (2) facilitate the formation of subsequent mental images, and (3) draw attention to additional, often implicit, relationships between the components of a problem. Preliminary drawings of six-membered phenyl rings and carboxylic acid groups do not necessarily free space in short-term memory, but they can facilitate the formation of the mental image of the product of this reaction and focus attention on the presence of the carbonyl group, which guides students towards the correct answer and away from unreasonable answers such as "PhCl" or "PhCOOCl".

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