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In the Classroom

The Purdue Visualization of Rotations Test

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We weren't surprised by either the magnitude or the statistical significance of the correlation between spatial ability and spatially oriented tasks in general chemistry.

This paper probes the relationship between the psychometric construct known as "spatial ability" and students' performance in introductory chemistry courses. It examines some of the early literature on the evolution of the concept of spatial ability, reviews the results of research on the relationship between success (or failure) in introductory chemistry courses and students' spatial ability, and describes a spatial ability test known as *The Purdue Visualization of Rotations* (ROT) test that has been shown to be among the spatial ability tests whose results are *least likely* to be complicated by analytical processing.

Introduction

The last requirement of the mandatory Air Force ROTC program in which the first author was enrolled during his freshman and sophomore years was the Air Force Officers Qualifying Test. This test included questions based on photographs of airplanes at various orientations that probed the

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individual's ability to predict the maneuvers needed to either intercept or avoid another plane. It also showed aerial photographs from which one was supposed to predict the maneuvers needed to bring a plane over a target from a particular direction.

These questions seemed trivial. Changes in the direction in which a plane flies can be thought of in terms of three modes of motion—pitch, yaw, and roll—and these questions seemed to require the same thought processes as the tasks he had encountered in his organic chemistry course, where he had to envision what happened when he rotated a mental image of a molecule. He wasn't surprised when he was told that he had scored at the 99th percentile on this portion of the test.

Slightly more than a decade later, the first author was an assistant professor in chemical education interested in the problems student face when they take first- and second-year chemistry courses. He reflected back on the ease with which he was able to handle spatial tasks in chemistry—whether they involved distinguishing between the *R* and *S* enantiomers of a molecule, recognizing the symmetry elements needed to assign a space group to a molecule, or visualizing the three-dimensional structure of organic molecules from two-dimensional representations shown on a computer screen. He then asked, "What role does spatial ability play in undergraduate chemistry courses? To what extent does the lack of spatial ability interfere with students' success in the first-and second-year courses that are required of so many people?"

Summary of Early Research

Preliminary research with a battery of spatial tests, including the Purdue Visualization of Rotations (ROT) test described in this paper, showed a highly significant correlation between spatial ability and spatially oriented tasks in general chemistry such as the following questions from a quiz on crystal structures [1].

1. A compound which contains Cs, Fe and F crystallizes in a cubic unit cell for which the cell edge is 0.6158 nm. The positions of the unique atoms are given below:

Cs: ½,½,½ Fe: 0,0,0 F: ½,0,0; 0,½,0; 0,0,½

How many net atoms of each type are contained within the unit cell? What is the empirical formula of this compound? What are the coordination numbers of the Cs and

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Fe atoms in this unit cell? Is this a simple cubic, body-centered cubic, or face-centered cubic unit cell? What is the Cs-F interatomic distance in this unit cell?

2. Tungsten crystallizes in a cubic unit cell with a cell edge of 0.3981 nm. The density of tungsten is 19.35 g/cm^3. Calculate the number of atoms per unit cell.

3. Calculate the atomic radius of the Ba atom if barium crystallizes in a face-centered cubic unit cell with a cell edge of 0.5060 nm.

A correlation was also seen between the students' scores on the spatial ability tests and their performance on the following questions from an hour exam.

1. Which figure[1] illustrates a simple cubic array of anions with one-half of the cubic holes occupied?

2. Titanium metal crystallizes in a body-centered-cubic unit cell. The distance between nearest titanium atoms is: (a) *a* (b) 1/2 *a* (c) 2/3 *a* (d) 3/2 *a* (e) none of these.

3. Calculate the fraction of empty space in a face-centered cubic unit cell.

The magnitude of the correlation between the students' performance on the spatial ability tests and their performance on a crystal structure quiz was reasonable (r = 0.35), as was the correlation with hour-exam questions that probed their understanding of crystal structures (r = 0.32), particularly when you consider that there were relatively few questions on either the quiz or the hour exam that dealt with this topic. The correlation was highly significant ($p < 0.0001$) because we were able to use a relatively large sample population in this study. The square of the correlation coefficient reflects the percentage of the variation in student scores that can be explained by students' spatial ability. In this case, slightly more than 12% of the variance can be explained by the spatial ability factor. The p-value suggests that there is only 1 chance in 10,000 that our conclusion that spatial ability was an important factor was in error.

[1]The figure that accompanied this exam question showed the unit cells of NaCl, ZnS, CsCl, CaF_2, and TiO_2.

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We weren't surprised by either the magnitude or the statistical significance of the correlation between spatial ability and spatially oriented tasks in general chemistry. We were surprised, however, when we found an equally significant correlation between the students' spatial ability scores and their performance on one of the least spatial aspects of our course, the following multiple-choice stoichiometry questions from the first exam.

1. The percent by mass of oxygen in sodium hydroxide is: (a) 0.410% (b) 0.575% (c) 40.0 % (d) 57.5% (e) 60.0%

2. What mass of calcium oxide can be prepared by ignition of 1.2577 g of calcium carbonate? (a) 0.01256 g (b) 0.5528 g (c) 0.7049 g (d) 0.9522 g (e) none of these answers is within ±5% of the correct value.

3. What is the concentration of Li_2HPO_4 in a solution produced by dissolving 0.173 g of Li metal in enough phosphoric acid to give 255 mL of solution?

$$2\ Li + H_3PO_4 \rightarrow Li_2HPO_4 + H_2$$

(a) 1.25×10^{-2} M (b) 2.5×10^{-2} M (c) 4.9×10^{-2} M (d) 9.8×10^{-2} M (e) The question cannot be answered without knowing the concentration of phosphoric acid.

4. What volume of gas at 0 ºC and 1 atm is produced by the decomposition of 2.39 g of $Cu(NO_3)_2$?

$$2\ Cu(NO_3)_2 \rightarrow 2\ CuO + 4\ NO_2 + O_2$$

(a) 286 mL (b) 571 mL (c) 714 mL (d) 1.43 L (e) 112 L

When we extended this work to organic chemistry [2], we found that up to 15% of the variance on hour exams could be attributed to spatial ability. A much more interesting phenomenon arose when we probed the relationship between students' spatial ability scores and their success on subscores calculated by selecting only a handful of items from a given hour exam. The correlation between spatial ability and students performance on chemistry exams was significant for questions that required problem-solving skills, such as completing a reaction or outlining a multistep synthesis, and questions that required students to mentally manipulate two-dimensional

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representations of a molecule. Spatial ability did not correlate, however, with performance on subscores that grouped questions that could be answered by rote memory or by applying a simple algorithm.

A similar result was found when we returned to general chemistry courses [3]. In this work, we grouped questions on 11 hour exams in three different courses into 35 subscores of closely related questions. One subscore, for example, was a total of the students' scores on five empirical formula questions from the first hour exam and the final exam, another subscore was the total of the students' scores on nine molecular geometry questions from the third hour exam and the final exam. Once again, a clear pattern surfaced. Statistically significant correlations were observed for subscores that grouped questions that were most likely to be *novel problems* for the students—questions that differed significantly from those the students had seen previously in the textbook, in lecture, or on homework assignments and, these correlations were no longer statistically significant when the subscore grouped questions that were routine exercises, similar to those they had encountered previously.

From the beginning of this work on the relationship between spatial ability and students' success (or failure) on quizzes and exams in introductory chemistry courses, it was apparent that strong correlations were observed under two independent conditions: when the chemistry task had a high spatial content, such as questions on the three-dimensional structure of crystals in general chemistry or on optical activity from organic chemistry exams, and when the question required the students to exercise true problem-solving skills.

We have therefore written extensively on the difference between the process by which students use algorithms or very simple problem-solving strategies to work routine exercises and the more complex—and more anarchistic—process they use when faced with questions that are novel problems [4, 5]. The spatial ability tests in our experiments measure the students' ability to disembed relevant information from a complex drawing or restructure this information. We therefore believe that the correlation between spatial ability and problem-solving performance in our studies results from the relative importance of preliminary stages of problem solving in determining whether a student is successful on tasks they encounter in their introductory courses, stages in which the relevant information must be disembedded from the statement of the problem and then transformed or restructured until the

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individual begins to understand the problem. These preliminary stages can be thought of as stages in which the first steps are taken toward building a mental representation of the problem.

As a result, we believe that tests of spatial ability, such as the ROT test described in this paper, can be used for a variety of purposes besides predicting which students will have difficulty with spatial tasks in chemistry or to probe which students might have difficulty abstracting relevant information from two-dimensional models projected on a computer screen. They can also be used to probe students' problem-solving ability.

Summary of Research on Tests of Spatial Ability

Spatial ability has been a source of controversy ever since the 1920s when argument focused on whether there was a separate spatial aptitude, or whether so-called "mechanical aptitude tests" were simply unreliable measures of general intelligence. Once the existence of spatial ability was generally accepted, debate turned to the number and identities of spatial factors [6–13].

The multitude of spatial factors that emerged from early factor-analysis studies was eventually reduced to two major factors: spatial orientation and spatial visualization [14]. The *spatial orientation* factor has been described as a measure of the ability to remain unconfused by changes in the orientation of visual stimuli, and therefore it involves only a mental rotation of configuration [15]. The *spatial visualization* factor measures the ability to mentally restructure or manipulate the components of the visual stimulus and involves recognizing, retaining, and recalling configurations when the figure or parts of the figure are moved [10].

Male superiority on spatial tasks has been described as the most persistent individual difference in the ability literature [16]. O'Conner [17], Anastasi [18], Smith [12], Tyler [19], Garai and Scheinfeld [20], Sherman [21], Buffery and Gray [22], Maccoby and Jacklin [23], Harris [24], and McGee [10] have all cited evidence for the existence of sex differences in spatial skills, and Maccoby and Jacklin [23] listed visual-spatial ability as one of only four sex differences that are fairly well established. Block [25], Fairweather [26], and Sherman [21] have noted weaknesses in these studies, however, Sherman [21] and Plomin and Foch [27] argued that statistically significant sex differences often account for only negligible fractions of the variance in ability. Thus,

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one of the questions that must be asked when considering gender effects that are "statistically significant" is whether the results are significant because of the size of the sample population or because of a truly significant separation of the curves that represent the male and female subsamples.

Debate about the number and identity of the factors defined by spatial tests or about the possible existence of gender effects are of less concern to the authors of this paper than the controversy about whether spatial tests actually measure the cognitive tasks generally recognized as spatial ability. Barratt [28] and French [29] noted that spatial tasks can often be solved in different ways, and suggested that the cognitive processing strategy used to answer the test determines the ability the task measures. Evidence that spatial tests may measure different abilities has been presented by Borich and Bauman [30] and Price and Eliot [31]. It has even been suggested that sex differences in spatial ability result from differences in the way spatial tasks are processed [32–34] rather than differences in spatial ability itself.

There is general agreement [12, 35] that two major processing strategies are used to solve spatial tasks: analytic processing versus gestalt processing. *Gestalt processing* occurs when an individual forms and transforms visual images as an organized whole—in much the same way that one recognizes faces. (It is a rare individual, indeed, who recognizes members of his or her family by focusing on the distance between their eyes, or the color of their eyes. In fact, it has been argued that many people cannot tell you the color of close relative's eyes.) *Analytic processing* occurs when the whole is broken into individual parts, whose relationship is mapped in a one-to-one process. The authors' concern with this dichotomy reflects the fact that holistic or gestalt processing has been widely accepted as the key cognitive component of spatial ability [12, 14, 36]. Yet, many spatial tests require only a minimal amount of gestalt processing and a significant amount of analytic processing [37].

The development of the test described in this paper was based on two assumptions: (1) that existing spatial ability tests vary in the degree to which they evoke the use of analytic versus gestalt processing, and (2) that tests that maximize gestalt processing while minimizing analytic processing are the best measures of spatial ability.

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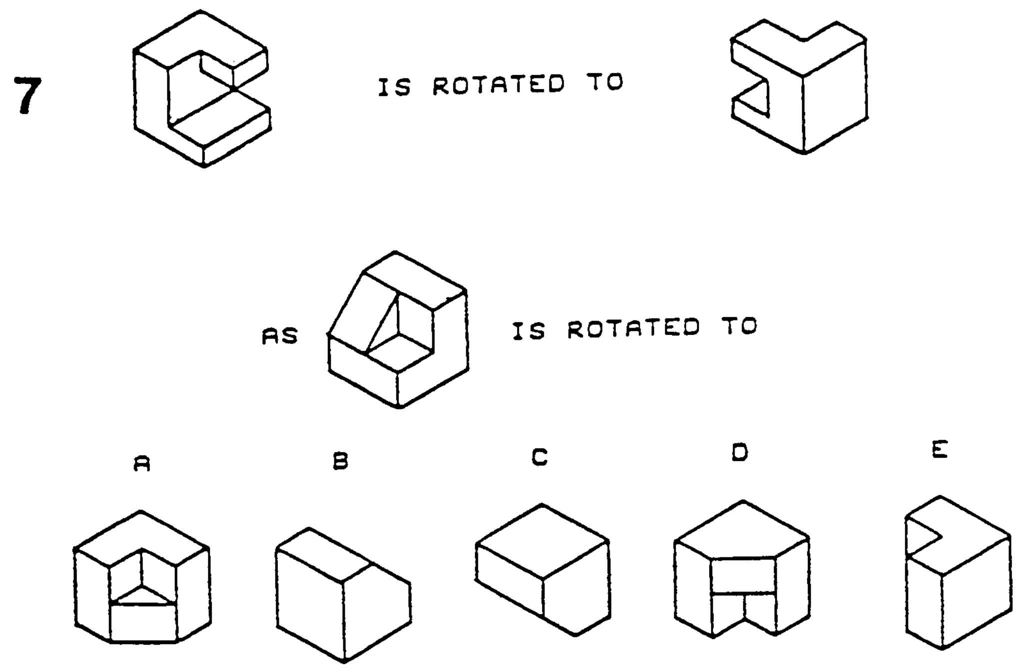

FIGURE 1. ITEM 7 FROM THE 20-ITEM VERSION OF THE PURDUE VISUALIZATION OF ROTATIONS (ROT) TEST. COPYRIGHT, PURDUE RESEARCH FOUNDATION.

The Purdue Visualization of Rotations Test

The Purdue Visualization of Rotations Test (ROT) is one element of the Purdue Spatial Visualization Test Battery [38]. Although it was originally developed as a 30-item test, a shorter 20-item version was constructed by removing questions 6, 8, 11, 14, 20, 21, 22, 24, 26, and 30. Item 7 from the 20-item ROT test is shown in Figure 1.

The directions for the ROT exam tell the student 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. To restrict analytical processing, a time limit of 10 minutes for the 20-item version of this test is strictly enforced.

ROT resembles the Shepard–Metzler (S–M) Rotations test adapted for group testing by Vandenberg [37], one item of which is shown in Figure 2. Both tests require mental operations on the mental representation of the object that are more analogous to

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manipulations of the three-dimensional object being represented than the two-dimensional drawings which are actually presented. ROT differs from S–M, however, in several ways. Whereas rotation in the Shepard–Metzler test is restricted to the plane of the drawing or a vertical axis running through the drawing, the axis of rotation in the ROT test corresponds to a natural axis of the object. Furthermore, whereas Shepard and Metzler [39] avoided drawings which contained singularities with hidden parts, the ROT exam contains questions in which characteristic aspects of the object are hidden from view, as can be seen in Figure 1. The ROT exam also contains questions in which the object is rotated around more than one axis.

Estimates of Test Reliability

Two questions must be answered when tests such as the ROT test are developed. Is the test reliable? (Are similar results obtained when the test is given to similar populations?) And, is the test valid? (Is the test a valid measure of the construct it claims to measure?)

The first step toward estimating the reliability of the 20-item version of the ROT test involved calculating the Kuder–Richardson 20 (KR-20) and/or split-half (SH) reliability coefficients given in Table 1, which suggest that the ROT test is internally consistent. These data were obtained in studies of more than 4,800 students at Purdue University enrolled in general chemistry (CHM 111 or 115) or organic chemistry (CHM 255 or 257) courses for either agriculture and health science or science and engineering majors [40–43].

Evidence for the reliability of the ROT test can also be obtained from the mean and standard deviation data for different populations given in Table 2, which reflect the precision of the ROT test. McMillen [42] and Carter [40] obtained virtually identical means and standard deviations when testing different groups of engineering and science majors enrolled in CHM 115 at Purdue, and Pribyl [43] obtained similar data in a sophomore organic chemistry course taken by biology or pre-med majors who had completed CHM 115. There was also reasonable agreement between the data obtained by McMillen [42] and LaRussa [41] for students enrolled in the CHM 111 course taken by agriculture and health science majors at Purdue and the data obtained by Pribyl [43] in the organic chemistry course taken by students who have completed CHM 111.

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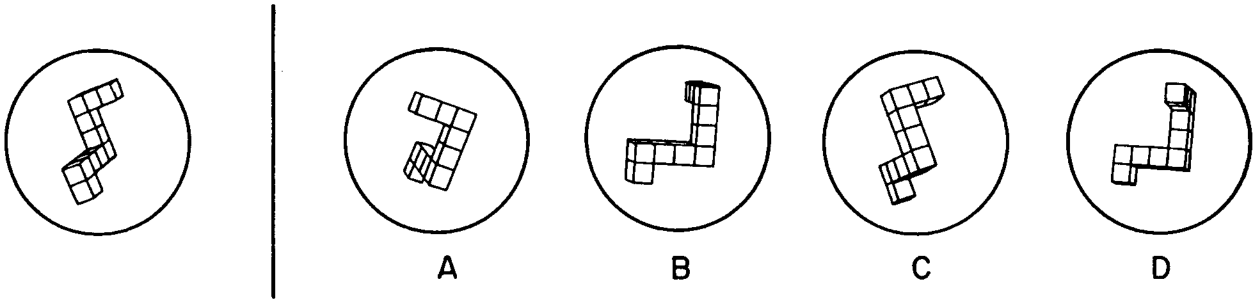

FIGURE 2. ONE ITEM FROM THE SHEPARD-METZLER (S-M) ROTATIONS TEST ADAPTED FOR GROUP TESTING BY VANDENBERG.

TABLE 1. The Number of Students and The Kuder–Richarson 20 or Split-Half Reliability Coefficients For The 20-Item ROT Test.

Study	*n*	KR_{20}	*SH*
CHM 111 (Ag/health science) [42]	757	0.80	0.83
CHM 111 (Ag/health science) [41]	850	0.78	0.80
CHM 257 (Ag/health science) [43]	127	--	0.84
CHM 115 (Science/engineering) [42]	1273	0.80	0.85
CHM 115 (Science/engineering) [40]	1648	--	0.82
CHM 255 (Biology/pre-med) [43]	158	--	0.78

Construct Validity of the ROT Test

To probe the construct validity of the ROT test, the 30-item version was used as one of five measures of spatial ability in a study of the relative importance of cultural and neurophysiological factors in spatial test performance [44]. The two most highly correlated spatial ability scores were on the ROT and Shepard–Metzler tests ($r = 0.61$, $p < 0.001$). The two least correlated scores were on the ROT and the Revised Minnesota Paper Form Board (MPFB) tests ($r = 0.25$, $p < 0.01$).

In a separate study, Guay, McDaniel, and Angelo [45] found that ROT and S–M were the spatial ability tests *least likely* to be confounded by analytical processing, whereas MPFB was the *most likely* to be confounded. Taped interviews suggested that MPFB is

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TABLE 2. Number of Students, Mean, and Standard Deviation Data For The 20-Item Purdue Visualization of Rotations Test.

Population	*n*	*Mean*	*Standard Deviation*
General chemistry course of science/engineering majors [42]	1273	13.84	3.84
General chemistry course of science/engineering majors [40]	1648	13.96	3.80
Sophomore organic course for biology/pre-med majors [43]	158	14.16	3.78
General chemistry course for agriculture/health science majors [42]	757	12.49	4.08
General chemistry course for agriculture/health science majors [41]	850	11.66	3.96
Sophomore organic course for agriculture/health science majors [43]	127	12.35	4.02

TABLE 3. Number of Students, Mean, and Standard Deviation Data For The ROT Test Divided by Gender.

	Males			*Females*		
	n	$\bar{x}$	σ	*n*	$\bar{x}$	σ
General chemistry course of science/engineering majors [40]	520	15.14	3.22	285	12.67	3.61
Sophomore organic course for biology/pre-med majors [43]	73	14.93	3.90	85	13.49	3.55
General chemistry course for agriculture/health science majors [41]	359	13.30	3.80	479	10.45	3.56
Sophomore organic course for agriculture/health science majors [43]	48	13.85	3.70	79	11.43	3.95

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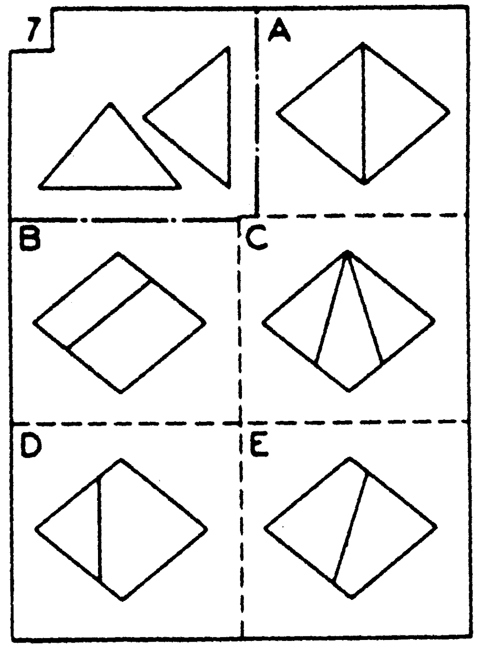

FIGURE 3. AN ITEM FROM THE MPFB TEST, WHICH ASKS FOR THE ALTERNATIVE THAT CORRECTLY SHOWS HOW THE PARTS GIVEN IN THE UPPER LEFT CORNER FIT TOGETHER.

often answered by an analytical process characterized by an explicit trial-and-error checking of relationships between different parts of a figure. To understand why students' scores on the MPFB can be influenced by their ability to handle spatial tasks by an analytical process, consider the example from the MPFB test given in Figure 3.

Sex Effects on Spatial Performance

Table 3 shows the difference in performance on the ROT test when the samples are divided on the basis of sex. In each case, males outscored females. But this still leaves two important questions: Is the difference statistically significant? And, is the difference large enough to have significant implications for those of us who teach chemistry? The first question can be answered by running simple statistical tests, such as a one-tailed *t* test, which asks: is the difference between the means of the male and female subpopulations statistically significant? Our results suggested that the difference was statistically significant at the $p < 0.0005$ level in all but the organic chemistry course for biology/pre-med majors, where $p < 0.01$. Furthermore, the differences are not only statistically significant, they are reasonably large. Carter [40] found that roughly three-quarters of the males scored at or above the female mean, and

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in all but one of these studies the difference between the male and female means is larger than two-thirds of the standard deviation of the scores.

Summary

Evidence which supports the hypothesis that the Purdue Visualization of Rotations test is a valid measure of the cognitive abilities most often described under the heading “spatial ability” is summarized below:

- the precision of mean and standard deviation data when the test is given to different samples of similar populations.
- the strong correlation between performance on ROT test and Shepard-Metzler tests, which have been shown to be among the spatial tests least likely to be confounded by analytic processing strategies.
- the much weaker correlation between performance on the ROT test and the Minnesota Paper Folding Board test, which has been shown to be among the spatial tests most likely to be confounded by analytic processing.
- the significant difference between the performance of males and females on the ROT test, which has been observed in other measures of the spatial visualization factor of spatial ability.
- the correlation between ROT scores and students’ performance on highly spatial topics in chemistry.
- the correlation between ROT scores and performance on problem-solving tasks in chemistry that require cognitive restructuring/disembedding strategies.

Copies of the 20-item Purdue Visualization of Rotations test and a scoring key can be obtained from the first author. They can also be downloaded from this journal’s abstract page for this article. Permission to use this test is freely granted. Reasons to use this test are many and varied. It can be used to diagnose students who might have difficulty in organic chemistry, biochemistry, or even general chemistry. It can be used as a research instrument for work on students’ abilities to use multiple representations or to probe alternative modes whereby students solve problems. It can be used to probe

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changes in gender effects on spatial ability. It can be used as the basis for evaluating courses [46] developed to enhance students' spatial skills. It can be used to probe students' perception of computer-based learning activities that require them to perceive three-dimensional structures from two-dimensional representations on a computer screen. Or, it could be used to probe what happens when students use the emergent technologies of VR and VRML software being developed.

It is worth noting that our work suggests that there is a significant population of chemistry majors—and practicing chemists—who have mediocre, if not poor, spatial skills. They have developed a variety of tricks to solve problems that can be as simple as turning the page in a book, holding the page up to a bright light, and looking *through* the paper to see what the stereoisomer of a molecule would look like. It is also worth noting that spatial ability is a skill that can be developed through practice [46, 47].

REFERENCES

1. Bodner, G. M.; McMillen, T. L. B. "Cognitive Restructuring as an Early Stage in Problem Solving" *Journal of Research in Science Teaching* **1986**, *23*, 727.

2. Pribyl, J. R.; Bodner, G. M. "Spatial Ability and its Role in Organic Chemistry: A study of Four Organic Courses" *Journal of Research in Science Teaching*, **1987**, *24*, 229.

3. Carter, C. S.; LaRussa, M. A.; Bodner, G. M. "A Study of Two Measures of Spatial Ability as Predictors of Success in Different Levels of General Chemistry" *Journal of Research in Science Teaching*, **1987**, *24*, 645.

4. Bodner, G. M. "The Role of Algorithms in Teaching Problem Solving" *Journal of Chemical Education*, **1987**, *64*, 513.

5. Bodner, G. M. "A View From Chemistry" In Smith, M. U., Ed.; *Toward A Unified Theory of Problem Solving: Views From the Content Domains*; Lawrence Erlbaum Associates: Hillsdale, NJ,.1991; pp 21–34.

6. French, J. W. "The Description of Aptitude and Achievement Tests in Terms of Rotated Factors" Psychometric Monograph #5, 1951.

7. Guilford, J. P.; Fruchter, B.; Zimmerman, W. S. "Factor analysis of the Army Air Forces, Sheppard Field Battery of Experimental Aptitude Tests" *Psychometrika* **1952**, *16*, 45.

8. Guilford, J. P.; Zimmerman, W. S. "Some A.A.F. Findings Concerning Aptitude Factors" *Occupations*, **1947**, *26*, 154.

ISSN 1430-4171
http://journals.springer-ny.com/chedr
S 1430-4171 (97) 04138-X

9. Guilford, J. P.; Lacy, J. I. "*Printed classification tests, AAF, Aviation Psychological Progress Research Report*; #5 U. S. Government Printing Office: Washington, DC, 1947.

10. McGee, M. G. *Human Spatial Abilities, Sources of Sex Differences*; Praeger: New York, 1979.

11. Slater, P. "Some Group Tests of Spatial Judgement or Practical Ability" *Occupational Psychology*, **1940**, *14*, 40.

12. Smith, I. M. "*Spatial Ability, Its Educational and Social Significance*" Robert R. Knapp: San Diego, CA, 1964.

13. Thurstone, L. I. "*Some Primary Abilities in Visual Thinking*", No. 59 University of Chicago Psychometric Lab: Chicago, IL, 1950.

14. Michael, W. B.; Guilford, J. P.; Fruchter, B.; Zimmerman, W. S. "The Description of Spatial-Visualization abilities" *Educational and Psychological Measurement*, **1957**, *17*, 185.

15. Ekstrom, R. B.; French, J. W.; Harman, H. H. *Manual for Kit of Factor Referenced Cognitive Tests*; Educational Testing Service: Princeton, NJ, 1976.

16. Bouchard, R. J., Jr.; McGee, M. G. "Sex Differences in Human Spatial Ability: Not an X-Linked Recessive Gene Effect" **1977**, *Social Biology*, *24*, 332.

17. O'Connor, J. *Structural Visualization*; Human Engineering Laboratory: Boston, 1943.

18. Anastasi, A. Differential Psychology: Individual and Group Differences in Behavior, 3rd ed.; Macmillan: New York, 1958.

19. Tyler, L. *The Psychology of Human Differences*, 3rd ed.; Appleton-Century-Crofts: New York, 1965.

20. Garai, J. E.; Scheinfeld, A. "Sex Differences in Mental and Behavioral Traits" **1968**, *Genetic Psychology Monographs*, *77*, 169.

21. Sherman, J. A. *On the Psychology of Women: A Survey of Empirical Studies*; Charles C. Thomas: Springfield, IL, 1978.

22. Buffery, A. W. H.; Gray, J. H. "Sex Differences in the Development of Spatial and Linguistic Skills" In Ounstead, C.; Taylor, D. C., Eds.; *Gender Differences: Their Ontogeny and Significance*; Churchill: London, 1972.

23. Maccoby, E. E.; Jacklin, C. N. *The Psychology of Sex Differences*; Stanford University Press: Stanford, CA, 1974.

24. Harris, L. J. "Sex Differences in Spatial Ability: Possible Environmental, Genetic, and Neurological Factors" In Kinsbourne, M. Ed.; *Asymmetrical Function of the Brain*. Cambridge University Press: New York, 1978.

ISSN 1430-4171
http://journals.springer-ny.com/chedr
S 1430-4171 (97) 04138-X

25. Block, J. H. "Issues, Problems, and Pitfalls in Assessing Sex Differences: A Critical Review of The Psychology of Sex Differences" **1976**, *Merrill-Palmer Quarterly*, *22*, 283.

26. Fairweather, H. "Sex Differences in Cognition" **1976**, *Cognition*, *4*, 231.

27. Plomin, R.; Foch, T. T. "Sex Differences and Individual Differences" *Child Development*, **1981** *52*, 383.

28. Barratt, E. "An Analysis of Verbal Reports of Spatial Problems as an Aid in Defining Spatial Factors" *The Journal of Psychology* **1953**, *36*, 17.

29. French, J. "The Relationship of Problem-Solving Styles to the Factor Composition of Tests" *Educational and Psychological Measurement* **1965**, *25*, 9.

30. Borich, G.; Bauman, P. "Convergent and Discriminant Validation of the French and Guilford-Zimmerman Spatial Orientation and Spatial Visualization Factors" *Educational and Psychological Measurement*, **1972**, *32*, 1029.

31. Price, L.; Eliot, J. "Convergent and Discriminant Validities of Two Sets of Measures of Spatial Orientation and Visualization" *Educational and Psychological Measurement*, **1975**, *35*, 975.

32. Allen, M. "Sex Differences in Spatial Problem-Solving Styles" *Perceptual and Motor Skills*, **1974**, *39*, 843.

33. McGlone, J.; Kertesz, A. "Sex Differences in Cerebral Processing of Visuospatial tasks" *Cortex*, **1973**, *9*, 313.

34. Yen, W. M. "Sex-Linked Major-Gene Influences on Selected Types of Spatial Performance" *Behavior Genetics*, **1975**, *5*, 281.35. Spearman, C.; Jones, L. *Human Abilities*; Macmillan: London, 1950.

35. Spearman, C.; Jones, L. *Human Abilities*; Macmillan: London, 1950.

36. Bock, R.; Kolakowski, D. "Further Evidence of Sex-Linked Major-Gene Influencing on Human Spatial Visualizing Ability" *American Journal of Human Genetics*, **1973**, *25*, 1.

37. Vandenberg, S. C. "Sources of Variance in Performance on Spatial Tests" In Eliot, J.; Salkind, N. J., Eds.; *Children's Spatial Development* Charles C. Thomas: Springfield, IL, 1975.

38. Guay, R. *Purdue Spatial Visualization Tests*; Purdue Research Foundation: West Lafayette, IN, 1977.

39. Shepard, R. N.; Metzler, J. "Mental Rotation of Three-Dimensional Objects" *Science*, **1971**, *171*, 701.

40. Carter, C. S. A Study of the Relationships Between Spatial Ability, Sex, and Success in General Chemistry. Unpublished Masters Thesis, Purdue University, 1984.

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41. LaRussa, M. A. Spatial Ability, Hemispheric Specialization and Achievement in Chemistry. Unpublished Masters Thesis, Purdue University, 1985.

42. McMillen, T. L. B. A Study of the Relationship Between Spatial Ability, Field Dependence-Independence, and Achievement in Chemistry. Unpublished Masters Thesis, Purdue University, 1983.

43. Pribyl, J. R. A Study of the Relationship Between Spatial Ability and Achievement in Two Organic Chemistry Courses. Unpublished Masters Thesis, Purdue University, 1984.

44. Guay, R.; McDaniel, E. *Correlates of Performance on Spatial Aptitude Tests*; Final report; U. S. Army Research Institute, 1978.

45. Guay, R.; McDaniel, E.; Angelo, S. Analytic Factor Confounding Spatial Ability Measurement. Presented at the American Psychological Association, Toronto, Canada, 1978.

46. Baartmans, B. G.; Sorby, S. A. *Introduction to 3-D Spatial Visualization*; Prentice Hall: Englewood Cliffs, NJ, 1996.

47. Battista, M.T.; Grayson, H. W.; Talsma, G. “The Importance of Spatial Visualization and Cognitive Development for Geometry Learning in Preservice Elementary School Teachers” *Journal for Research in Mathematics Education*, **1982**, *13*, 32.