Transforming Spatial Reasoning Skills in the Undergraduate Geoscience Classroom Through Interventions Based on Cognitive Science Research

Carol J. Ormand, SERC, Carleton College & Geoscience, University of Wisconsin-Madison
Thomas F. Shipley, Psychology, Temple University
Basil Tikoff, Geoscience, University of Wisconsin-Madison
Cathryn A. Manduca, SERC, Carleton College
Barbara Dutrow, Geology & Geophysics, Louisiana State University
Laurel Goodwin, Geoscience, University of Wisconsin-Madison
Thomas Hickson, Geology, University of St. Thomas
Kinnari Atit, Psychology, Temple University
Kristin Michod Gagnier, Psychology, Temple University
Ilyse Resnick, Psychology, Temple University

ED31C-0757

Context

Spatial visualization is an essential skill in many, if not all, STEM disciplines. It is a prerequisite for understanding subjects as diverse as fluid flow through 3D fault systems, magnetic and gravitational fields, atmospheric and oceanic circulation patterns, cellular and molecular structures, engineering design, topology, and much, much more. Fortunately, spatial thinking improves with practice, and can improve more rapidly with intentional teaching and learning (e.g. Sorby, 2009).

Undergraduate geoscience students, including majors, bring a wide range of spatial visualization skill levels to the classroom (Figure 1). In addition, individuals excel at some spatial tasks while struggling with others (Figure 2).

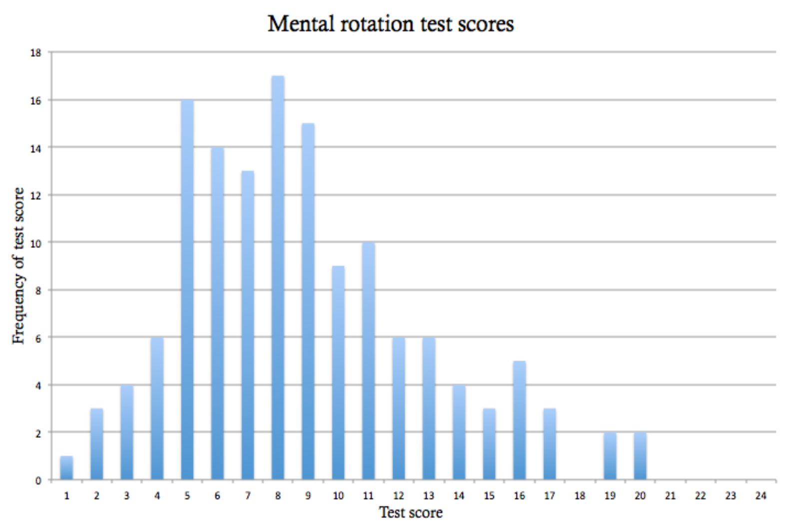


Figure 1. Examples of distributions of Vandenberg & Kuse Mental Rotation Test scores for students in Mineralogy, Structural Geology, and Sedimentology & Stratigraphy courses.

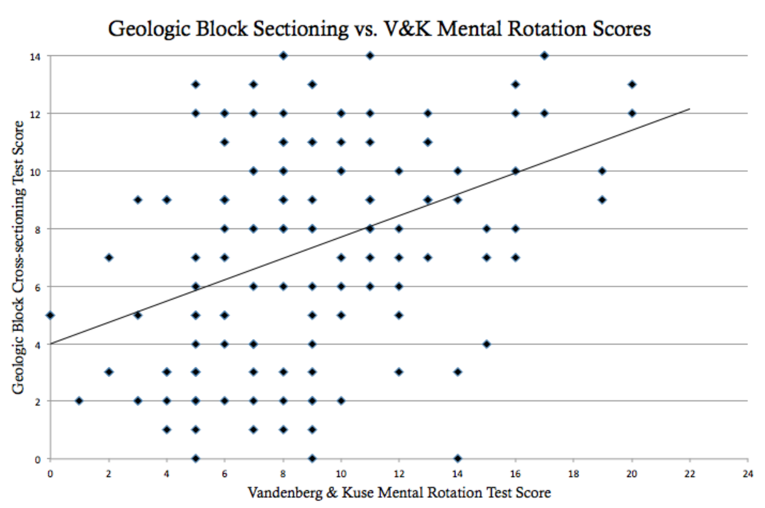


Figure 2. Scores on the Geologic Block Cross-sectioning Test vs. the Vandenberg & Kuse Mental Rotation Test (N=142). Although R=0.40, indicating a statistically significant correlation of these two skills, some students who excel at visualizing a cross-section through a geologic block diagram have difficulty visualizing mental rotations.

As a group of geoscientists and cognitive psychologists, we are collaborating to apply the results of cognitive science research to the development of teaching materials for geoscience courses. Our goal is to improve undergraduate geology students' spatial visualization skills.

Applying Strategies from Cognitive Science Research to Geoscience

3D Sketching and Prediction

Sorby (2009) showed that sketching in 3D improves spatial visualization skills and results in higher rates of success in undergraduate engineering courses. Similarly, making predictive sketches about the interior of an object (Figure 3), and immediately seeing the correct answer, boosts performance on tests of penetrative thinking: the ability to visualize the interior of an object (Gagnier et al., in review).

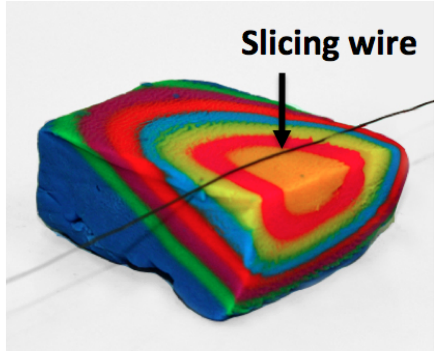


Figure 3. Students sketch what they think a play-doh model of a geologic structure will look like after being cut by the wire. They then see the sliced block and compare it to their prediction. Practice making predictive sketches, such as these, boosts students' performance on penetrative thinking tests.

As experts, we often look at a 2D exposure of a geologic feature and imagine its 3D form. Making 3D sketches may help students to make the same connections (Figure 4). In addition to giving students opportunities to practice sketching, we have video tutorials showing them how we construct our 3D sketches.

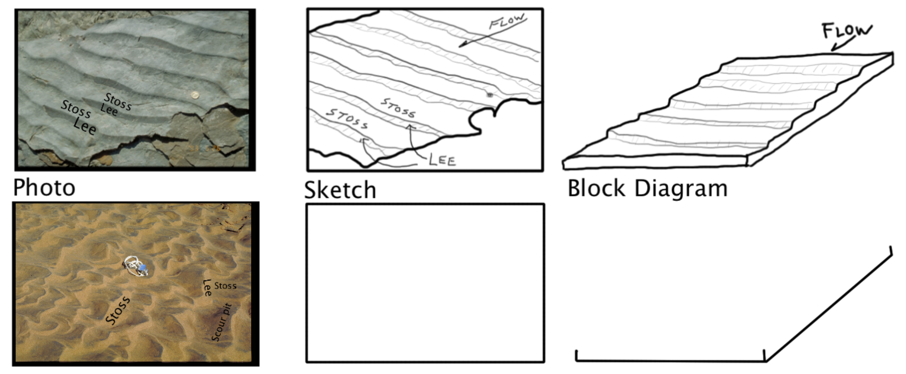


Figure 4. Top row: photo of sedimentary ripples and instructor's 2D and 3D sketches of them. Bottom row: photo of ripples and spaces for student's 2D and 3D sketches.

Analogy

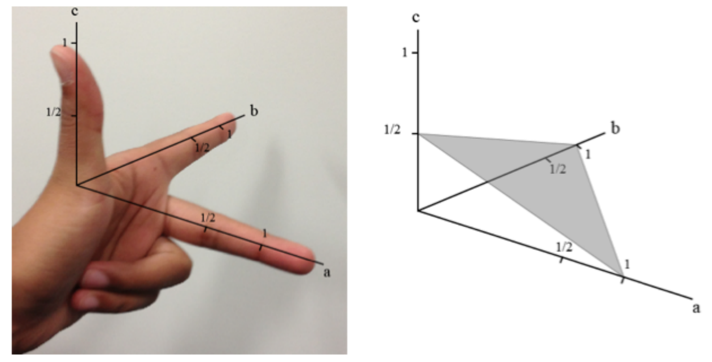
Analogies can help us to use what we know about familiar objects to make predictions about and develop our understanding of less familiar objects (Gentner, 1983). Fruit salad shares some key characteristics with a bowl of rocks, and a conglomerate is similar to a bowl of rocks and sand. Thinking about these similarities may help students to visualize the interiors of rock units (Figure 5).

Figure 5. Photos of fruit salad, a bowl of rocks, a bowl of rocks and sand, and a conglomerate.

Gesture

Students who gesture about spatial relationships perform better on spatial visualization tests than students who don't gesture, perhaps because gesture provides a mechanism for cognitive offloading (Goldin-Meadow et al., 2001). We have devised gesture exercises to help students master spatially challenging concepts (Figure 6) and to confront spatial misconceptions (Figure 7).

Figure 6. In Mineralogy, many students struggle to understand Miller Indices. In this exercise, students use one hand to gesture crystallographic axes and the other hand to gesture the orientations of various crystallographic planes. Working in teams, students check each other's gestures for accuracy.



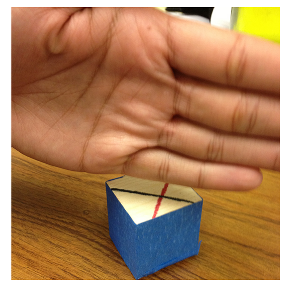


Figure 7. Many students assume that surficial features go "straight in," particularly at the hand sample and outcrop scales. In this exercise, students gesture their predictions of how surficial features will go into wooden blocks. They then unwrap the blocks to test their predictions.

Progressive Alignment

Making visual comparisons of similar objects or structures helps learners to identify key differences. Progressing from comparisons of very similar objects to less similar objects scaffolds the ability to identify salient features (Gentner et al., 2007).

Mineralogy students may not immediately recognize key features of 3D crystallographic structures. We have students compare pairs of minerals, starting with extremely similar pairs and moving to more dissimilar pairs, to identify those important characteristics (Figure 8).

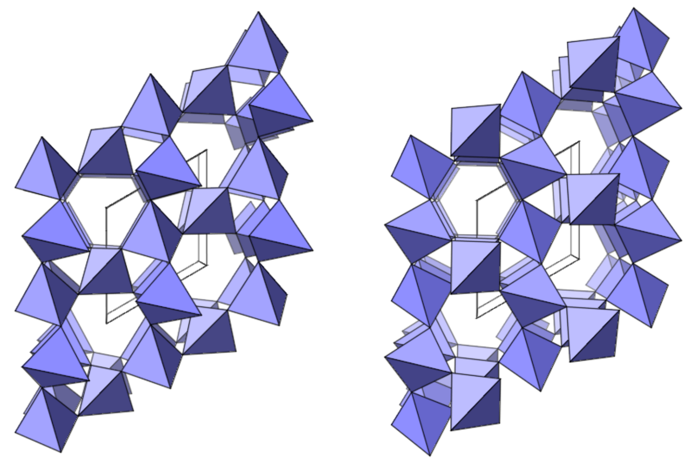


Figure 8. Representations of low-temperature (left) and high-temperature (right) polymorphs of quartz. High-temperature quartz has a higher degree of symmetry than low-temperature quartz, and this affects their physical properties. These images were produced using CrystalMaker software.

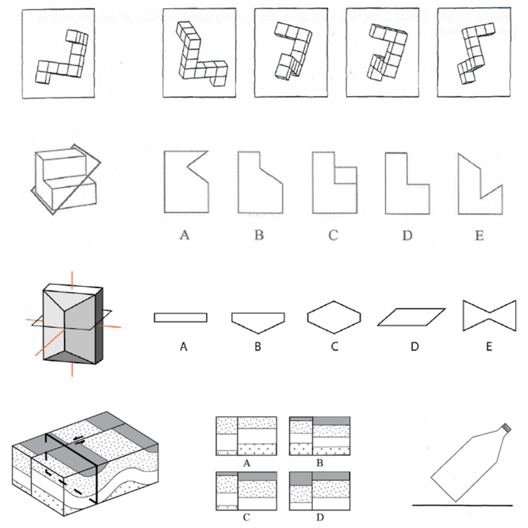
http://serc.carleton.edu/spatialworkbook/index.html

Preliminary Results

Baseline Data

In 2011-2012, we collected baseline data from each of three undergraduate geology courses: Mineralogy, Sedimentology & Stratigraphy, and Structural Geology. We administered pre- and post-test measures of spatial thinking: mental rotation, mental slicing, and water level (Figure 9). We used these to quantify the improvements in spatial thinking associated with taking each of these courses, without the exercises we developed.

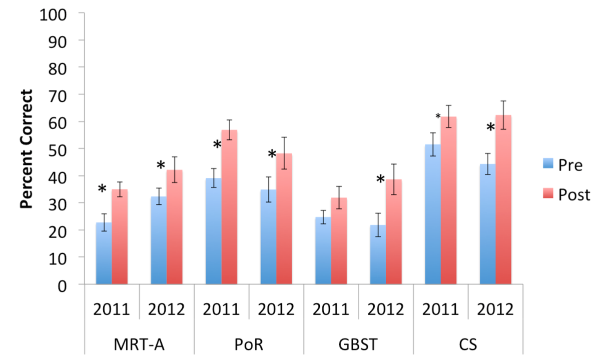
Figure 9. Example problems from the Vandenberg & Kuse (1978) mental rotation test: choose the two rotated versions of the image on the left; the Planes of Reference test (Titus and Horsman, 2009): choose the shape of the intersection of the slicing plane with the object; our Crystal Slicing Test: choose the shape of the intersection of the slicing plane with the crystal; our Geologic Block Cross-sectioning Test: choose the correct cross-section; and the Piaget water level test (Piaget and Inhelder, 1967): draw the top surface of water in this half-full bottle.



Effect of the Exercises

In 2012-2013, we administered the same pre- and post-tests in Mineralogy and Structural Geology, and also implemented several exercises employing gesture, progressive alignment, and analogy in those courses. In 2013-2014, we are adding sketching exercises as well. Our preliminary data suggest that these exercises can boost students' spatial thinking skills beyond the baseline gains we have measured in the same courses without the new exercises (Figure 10).

Figure 10. Comparison of spatial skills test results for baseline year and an intervention year, in our Mineralogy course: students gain spatial thinking skills over the course of a semester of Mineralogy, with or without our exercises. Some gains in the intervention year are statistically greater than baseline gains.



References

Gagnier, Kristin, Kinnari Atit, Carol J. Ormand, and Thomas F. Shipley. Comprehending Diagrams: Sketching to Support Spatial Reasoning. Manuscript in review.

Gentner, Dedre (1983). Structure-Mapping: A Theoretical Framework for Analogy. *Cognitive Science*, v. 7, pp. 155-170.

Gentner, Dedre, J. Loewenstein and B. Hung (2007). Comparison Facilitates Children's Learning of Names for Parts. *Journal of Cognition and Development*, v. 8, n. 3, pp. 285-307.

Goldin-Meadow, Susan, Howard Nusbaum, Spencer D. Kelly, and Susan Wagner (2001). Explaining Math: Gesturing Lightens the Load. *Psychological Science*, v. 12, n. 6, pp. 516-522.

Piaget, J. and B. Inhelder (1967). "Systems of Reference and Horizontal-Vertical Coordinates" (pp. 375-418) *in* The Child's Conception of Space. New York: W.W. Norton and Co.

Sorby, Sheryl (2009). Educational Research in Developing 3-D Spatial Skills for Engineering Students. *International Journal of Science Education*, v. 31, n. 3, pp. 459-480.

Titus, S.J. and E. Horsman (2009). Characterizing and improving spatial visualization skills. *Journal of Geoscience Education*, v. 57, pp. 242-254.

Vandenberg, S.G. and A.R. Kuse (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, v. 47, pp. 599-604.

This project is sponsored by NSF.